

Improving *Eucalyptus nitens* for sawn-board, veneer and paper products

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Contents

Statement of originality	ii
Authority of access.....	ii
Statement regarding published work contained in this thesis.....	ii
Statement of co-authorship.....	ii
List of figures.....	vi
List of tables	vii
Publications and other outcomes from studies conducted in this thesis	viii
Journal articles	viii
Conference proceedings	viii
Presentations	viii
Posters	viii
Abstract	ix
Acknowledgements	xi
1.0 Chapter 1. Introduction.....	1
1.1 Aims of the thesis with reference to chapters	6
2.0 Chapter 2. Resources, wood properties and products	7
2.1 Resources	7
2.2 Wood properties	9
2.2.1 Tree breeding for improved wood properties	9
2.2.2 Target breeding traits and selection criteria	11
2.3 Products	19
2.3.1 <i>Eucalyptus nitens</i> sawn board products.....	19
2.3.2 <i>Eucalyptus nitens</i> engineered wood products.....	20
2.3.3 <i>Eucalyptus nitens</i> pulpwood products.....	21
3.0 Chapter 3. Improved methods for achieving traceability of tree and log identities in timber processing studies.....	23
3.1 Introduction	23
3.2 Methods	26
3.2.1 Maintaining tree identity of harvested logs.....	26
3.2.2 Log Identification at the sawmill	31
3.2.3 Sawn-board identification	33
3.3 Discussion	35
4.0 Chapter 4. Stiffness and checking of <i>Eucalyptus nitens</i> sawn boards: genetic variation and potential for genetic improvement.....	38
4.1 Introduction	38
4.2 Materials and methods	40

4.2.1	Progeny trial	40
4.2.2	Tree selection and processing	40
4.2.3	Assessment of acoustic wave velocity and stiffness.....	42
4.2.4	Assessment of basic density and checking.....	42
4.2.5	Statistical analyses	44
4.3	Results and discussion.....	45
4.3.1	Basic density	49
4.3.2	Acoustic wave velocity and stiffness	49
4.3.3	Checking.....	51
4.4	Conclusion	53
5.0	Chapter 5. Genetic variation in traits affecting sawn timber recovery in plantation grown <i>Eucalyptus nitens</i>	55
5.1	Introduction.....	55
5.2	Materials and methods	59
5.2.1	Progeny trial	59
5.2.2	Tree assessment and selection.....	59
5.2.3	Assessment of log-end splitting and log taper	60
5.2.4	Log processing and assessment of log and green board volume	61
5.2.5	Statistical analyses.....	62
5.3	Results	65
5.4	Discussion	70
5.5	Conclusion.....	72
6.0	Chapter 6. Genetic correlations between pulpwood and wood stiffness appear favourable in <i>Eucalyptus nitens</i>	74
6.1	Introduction.....	74
6.2	Materials and methods	79
6.2.1	Progeny trial	79
6.2.2	Tree assessment, selection and processing	80
6.2.3	Assessment of acoustic wave velocity and stiffness.....	81
6.2.4	Assessment of basic density	81
6.2.5	Assessment of kraft pulp yield and cellulose content.....	82
6.2.6	Statistical analyses	82
6.3	Results	85
6.4	Discussion	88
6.4.1	Genetic variation in traits.....	88
6.4.2	Correlations among traits	91
6.4.3	Implications for the non-destructive assessment of progeny traits	93
6.5	Conclusion	94

7.0	Chapter 7. Discussion and Conclusion	95
7.1	Introduction	95
7.2	Genetic control of selection criteria and objective traits	96
7.2.1	Analysis of genetic variation in criteria and traits under study	96
7.2.2	Genetic control among and within races	99
7.2.3	Predicted genetic gains	103
7.2.4	Inter-trait genetic correlations	104
7.3	Key findings from conducted studies	107
7.4	Concluding remarks	108
8.0	References	111

List of figures

Figure 2.1	Map of Tasmania showing the Tarraleah <i>E. nitens</i> progeny trial location	8
Figure 2.2	Geographical and genetically distinct localities of the Connor's Plain, Northern and Southern Central Victorian <i>E. nitens</i> races where trial seed was selected from. Figure modified from Hamilton et al. (2008)	8
Figure 2.3	NIR prediction of cellulose content. Graphs above were captured from trial assessments using OPUS 5.5 (Bruker, 2005) ..	15
Figure 2.4	Checking expressed radially by differential shrinkage in wood disks (above upper), on a machined board surface (left) and internally in a wafer extracted from the machined board (right)	16
Figure 2.5	Machined board under an applied load for static MOE testing.....	17
Figure 2.6	Log-end splitting in <i>E. Nitens</i>	18
Figure 2.7	Typical use of the <i>E. nitens</i> solid wood products manufactured from sawn-board and veneer sheet, examined in studies undertaken during this thesis.	21
Figure 3.1	Standing tree identification method with a white band indicating identification-plug position.....	27
Figure 3.2	Identification-plug installed.....	30
Figure 3.3	Attached log-end templates	33
Figure 3.4	Template sections remaining on board after final machining	34
Figure 4.1	Reference wedges used for the internal visual assessment of internal wedge check scoring	43
Figure 5.1	Log cutting patterns (A-E)	62
Figure 7.1	Estimated family within race additive genetic correlations between standing tree acoustic wave and both pulpwood and sold-wood traits.	105

List of tables

Table 4.1	Estimated Race means, F-ratio of difference among races, overall least-squares mean, additive variance, narrow-sense heritability (h_{op}^2) and coefficient of additive variation (CV_{add}) for each trait.	47
Table 4.2	Inter-trait genetic (below diagonal) and phenotypic (above diagonal) correlations with standard errors shown in parentheses.	48
Table 5.1	Log dimensions, number of logs processed, rankings of mean stem straightness, number of green boards extracted and their dimensions for each cutting pattern.	62
Table 5.2	Race least-square means, P-values (to test the significance of race differences), overall trial mean, additive variance, narrow-sense heritability (h_{op}^2) and coefficient of additive variation ($CV_{add}\%$) for studied traits, with standard errors in parenthesis	67
Table 5.3	Inter-trait genetic and phenotypic correlations with standard errors in parenthesis. Additive genetic correlations involving stem taper and green-board volume were not calculated as no significant additive genetic variation was detected for these traits.....	68
Table 5.4	Means of recovery traits for different log cutting patterns with standard errors in parenthesis. Common letters indicate treatments that are not significantly different ($P < 0.05$), following a Turkey-Kramer adjustment for pairwise comparisons	69
Table 6.1	Estimated Race means, F-ratio of difference among races, overall least-squares mean, additive variance, narrow-sense heritability (\hat{h}_{op}^2) and coefficient of additive variation (\widehat{CV}_{add}) for each trait.....	86
Table 6.2	Inter-trait phenotypic and genetic correlations with standard errors shown in parentheses	87
Table 7.1	Estimated genetic parameters and potential gains relative to responses. In selection, for all traits under study in this thesis	99

Publications and other outcomes from studies conducted in this thesis

Journal Articles

- BLACKBURN, D. P., HAMILTON, M. G., HARWOOD, C. E., INNES, T. C., POTTS, B. M., WILLIAMS, D. 2010. Stiffness and checking of *Eucalyptus nitens* sawn boards: Genetic variation and potential for genetic improvement. *Tree Genetics and Genomes*, 6, 757-765.
- BLACKBURN, D. P., HARWOOD, C., INNES, T. & WILLIAMS, D. 2011. Traceability of trees and log identities in timber processing studies. *Forest Products Journal*, 60.
- BLACKBURN, D. P., HAMILTON, M. G., HARWOOD, C. E., INNES, T. C., POTTS, B. M., WILLIAMS, D. In-press. Genetic variation in traits affecting sawn timber recovery in plantation grown *Eucalyptus nitens*. *Annals of Forest Science*. DOI: 10.1007/s13595-011-0130-y

Conference Proceedings

- BLACKBURN, D. P., HARWOOD, C., HAMILTON, M. G., INNES, T. C., POTTS, B. M., WILLIAMS, D. 2009. Genetic variation in wood stiffness and sawn board checking traits in *Eucalyptus nitens*. In 'Australasian Forest Genetics Conference'. Forest Products Commission, Perth, Australia, April 2009.
- SOUTHERTON, S.G., WILLIAMS, D., JOYCE, K., RAVENWOOD, I., MEDER, R., BLACKBURN, D., MACMILLIAN, C.P., ZHANG, D., BELL, J.C., BHUIYAN, N., THUMMA, B.R. 2009. Association of allelic variation in xylem genes with wood properties in *Eucalyptus nitens* (Deane & Maiden). In: Taking care of business, Proceedings 2nd Australasian Forest Genetics Conference (Fremantle, Australia, 20-22 April, 2009)

Presentations

- BLACKBURN, D. P. 2010. Genetic variation in plantation grown *Eucalyptus nitens* for wood products. In 'Wood quality workshop - Review of research progress and prospects for solid and engineered wood products from plantation-grown *Eucalyptus nitens* and *E. globulus*'. CRC for Forestry, Hobart, Tasmania.
- BLACKBURN, D. P. 2011. Genetic variation in solid-wood and pulpwood properties in *Eucalyptus nitens*. In 'Southern Tree Breeders Association's Annual Science Meeting 2011'. University of Melbourne, Melbourne, Victoria.

Posters

- BLACKBURN, D. P., HAMILTON, M. G., HARWOOD, C., WILLIAMS, D., INNES, T. C., POTTS, B. M. 2007. Plantation Premiums – Breeding objectives for improving solid wood products manufactured from *Eucalyptus nitens* and *E. globulus*. Conference Posters In 'Plantation eucalypts for high-value timber'. Moorabin, Victoria.
- BLACKBURN, D. P., HAMILTON, M. G., HARWOOD, C., DOWNES, G., WILLIAMS, D., INNES, T. C., POTTS, B. M. 2008. Breeding objectives for solid wood products from plantation grown *Eucalyptus nitens*. In 'CRC for Forestry Annual Science Meeting'. Launceston, Tasmania.
- BLACKBURN, D. P., HAMILTON, M. G., HARWOOD, C., WILLIAMS, D., INNES, T. C., POTTS, B. M. 2010. Genetic variation in wood stiffness and sawn board checking traits in *Eucalyptus nitens*. In 'CRC for Forestry Annual Science Meeting'. Freemantle, Western Australia.

Abstract

Eucalyptus nitens is widely planted for pulpwood, and increasingly also for solid-wood timber products, in cool-temperate climates. This thesis investigated the potential of tree breeding to improve the properties of *E. nitens* grown for sawn boards, pulpwood and veneer products.

Two studies were undertaken using a 14 -15 year old *E. nitens* provenance-progeny trial established in Tasmania and comprising 420 open-pollinated families collected from three native races. In the first study, methods were developed to track the identities of 560 pedigreed trees through harvesting, transportation and sawmill processing. A second study tracked 548 trees from the same trial through a rotary peeled veneer production system. Genetic parameters were estimated for a total of 20 tree, log and wood traits relevant to sawn board, veneer and pulpwood products.

Genetic differences among races of *E. nitens* were significant in wood stiffness, growth, stem form and pulpwood traits, but not significant for log end-splitting and sawn board checking traits. The Southern race had the most favourable mean values. Significant additive genetic variation within races was observed in all traits except log-taper, demonstrating that the quality of plantation-grown *E. nitens* wood products could be improved through breeding.

Strongly positive genetic correlations among diameter at breast height (DBH) at ages 4, 9 and 14 years and between DBH all ages and the traits survival, log volume and stem straightness, demonstrated that early-age selection for DBH would not compromise stem straightness and would improve product volume recovery. Log end-splitting was under moderate genetic control but there was a negative genetic correlation between end-splitting and solid-wood product volume.

Sawn board and veneer sheet stiffness was highly heritable, and strongly correlated with acoustic wave velocity (AWV), measured in standing trees and logs. Consistent with previous studies in *E. nitens*, wood basic density, near infra red-(NIR) predicted kraft pulp yield (KPY) and cellulose content (CC) had moderate-to-high heritabilities, although coefficients of additive genetic variation for these traits were small.

Estimated genetic correlations between standing tree AWV and each of the traits veneer sheet modulus of elasticity (MOE), sawn-board MOE, KPY, CC and basic density were highly significant and strongly positive, suggesting that standing tree AWV could be adopted as an indirect non-destructive selection criterion for improving solid-wood product stiffness, while simultaneously improving wood chemical traits favoured by the pulpwood industry. Basic density had no significant genetic relationship with KPY and CC, although other studies have reported moderate to strong significant values.

Surface and internal checking in sawn boards, which are important defects leading to value downgrade, were shown to be under moderate levels of additive genetic control. Internal checking in wedges cut from log disks and in wafer sections cross-cut from processed boards were strongly and positively genetically correlated. However, the genetic correlation of checking traits with density and AWV were generally not significant.

Work presented in this thesis clearly demonstrates the potential for genetic improvement of *E. nitens* for pulpwood, sawn-boards and veneer production. A new method of tracking trees in processing studies has been established. Methods for assessing checking have been developed, and the utility of non-destructive AWV and NIR techniques has been confirmed for use in *E. nitens* breeding programs, aiming to simultaneously improve the quality and recovered volume of pulpwood and solid-wood products.

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1.0 CHAPTER 1. INTRODUCTION

Native trees of the genus *Eucalyptus* vary in architecture and form, from the tall and straight Shining Gum (*Eucalyptus nitens*) of the wetter highland regions of Victoria and New South Wales, to the multi-stemmed dwarf mallee species of the Australian desert (Boland et al., 1992). Commercially it is the world's most widely planted hardwood genus. In the early 20th century wide scale plantations were established in tropical and sub-tropical regions to provide pulplogs for the paper industry (Donnelly et al., 2003) and until the mid 1990's almost all the wood from eucalypt plantations was utilised as pulpwood, fuelwood or small poles, although the concept of producing high-value timber from eucalypt plantations has been discussed and promoted for decades (Tepper, 2007). Since this period there has been a decline in the availability of logs from natural forests and with improved processing technologies the economics for plantation grown timber for solid-wood products is increasingly favourable (Donnelly et al., 2003).

Globally today over 20 million hectares of eucalypt plantations have been established with India, China and Brazil accounting for more than fifty percent of that total area (GIT-Forest-Consulting, 2009). Because of their fast growth rate, good-form and excellent solid-wood and fibre properties the US Department of Energy has recognised many species of the genus for their biomass production and carbon sequestration capabilities. The eucalypt genome has now been successfully sequenced by a team of researchers led by Professor Myburg at the University of Pretoria. This achievement will lead to a better understanding of how its superior genes influence these desirable characteristics (University of Pretoria, 2011).

In Australia before the 1990's, state governments were the main plantation owners, but since then most of the investment in new plantations has been from privately funded managed investment schemes, most of which are looking for short-term returns on investment from plantation trees specifically

grown under silviculture regimes to produce small-diameter pulplogs for paper products, generally in a ten-to-fifteen year rotation (Lott and Gooding, 2007).

Australia currently runs an annual wood and wood products trade deficit of nearly \$2 billion dollars (Bureau of Rural Sciences, 2010), so provided it can be achieved profitably, growing and processing plantation timber to replace presently imported wood products will support a sustainable timber industry and assist in Australia becoming internationally competitive. Plantation timber also has the potential to replace the log supply for solid-wood products from native forests, which may allow Australia to set aside more forest area for conservation reserves. Presently approximately half of Australia's total plantation area of over 2 million hectares is hardwood and this is increasing annually, although growth has declined to less than one-percent in the last two years (Gavran and Parsons, 2011). Tasmania has a hardwood plantation area of approximately 234 000 ha of which *Eucalyptus nitens* covers 207 000 ha (Gavran and Parsons, 2011).

Eucalyptus nitens (Dean & Maiden) Maiden belongs to the subgenus *Symphyomyrtus*, section Maidenaria, subsection Euryotae, series Globulares (Brooker, 2000); and originates from south-eastern Australia. It is native to the cool, wet temperate regions of Australia, growing naturally in the Central Highlands of Victoria and nearby mountainous regions of southern NSW, with outlying populations occurring at higher elevations near Barrington Tops and Dorrigo in New South Wales (Boland et al., 1992, Hamilton et al., 2008).

The mean annual rainfall in the natural range of *E. nitens* is between 750 – 1750 mm with an even annual distribution (Boland et al., 1992). The species is less tolerant to water stress in dry conditions than *E. globulus* (Battaglia, 2006). Compared to *E. globulus*, *E. nitens* is highly resistant to the fungal leaf infection *Mycosphaerella* (Gadgil et al., 2000, Carnegie, 2007) which often limits the growth of *E. globulus* (Mohammed et al., 2003) and is widespread in the coastal areas of South Eastern Australia.

Eucalyptus nitens is the second most widely planted plantation eucalypt species in Australia (Gavran and Parsons, 2011) planted where low temperatures (Tibbits and Hodge, 2003) restrict the growth or survival of *E. globulus* (the most widely planted eucalypt species in Australia), and evidence suggests that a relative uniform seasonal distribution of rainfall is critical to its performance in plantations (Tepper, 2007). Most plantation managers preferring sites that receive an annual rainfall in excess of 850 mm (Laffan, 2002). The advantage of plantation-grown *E. nitens* for sawn timber products in cooler temperate regions of Australia is its good productivity and stem form on frost prone and often exposed sites with low mean annual temperatures, and Battaglia (2006) suggests that *E. nitens* can be highly productive at a mean annual temperature range of 9–12°C.

In Tasmania low nitrogen availability often limits the growth of *E. nitens* plantations on ex-forest sites, but generally ex-pasture sites will not require fertiliser due to their history of previous application (Smethurst, 2006). Reid (2007) reports that borer attack can contribute to the lower recovery of select-grade timber from plantation-grown trees, relative to that from native forest regrowth. Other studies have suggested that silvicultural practices, such as thinning to reduce water stress, may leave trees less susceptible to attack (Phillips, 1996).

Currently most plantations in Australia have been established to supply pulplogs, with the supply of sawlogs from plantations estimated to slowly rise to 2030 (Bureau of Rural Sciences, 2009). With a recent increase in planting, thinning and pruning of *E. nitens* plantations in Tasmania, Forestry Tasmania aims to supply approximately 150 000 m³ year⁻¹ of hardwood sawlogs by 2025 and the forecast is that the supply will continue until at least 2094 (Wood et al., 2009). The major challenge now is to optimise the management and returns from *E. nitens* sawlog plantations to influence the financial return an investor can expect (West, 2006). Sawlog plantations require different silvicultural regimes to pulpwood plantations, and these are now relatively

well established following research into factors such as thinning (Forrester and Baker, 2005) and pruning (Nolan et al., 2005, Beadle et al., 2007). The use of decision support systems that incorporate information on these factors will be critical in choosing the most appropriate management regime for each plantation site (Wood et al., 2009).

The main driver of site selection for a particular species is the overall return that can be achieved by investors in a plantation, often measured as a net present value per hectare (ha) over a rotation. Climate and environmental factors largely influence which species will provide the greatest return at any given plantation site, although these temperate eucalypt species will not provide a quality of wood that can be sawn for higher value appearance products in a ten-to-fifteen year period. To produce logs with defect-free clear wood suitable for processing into appearance-products it would take twenty to twenty-five years on a productive site (Wood et al., 2009).

The growing of timber in a plantation is the same as any other business where money originally invested has to be discounted for future returns, thereby requiring a greater rate of return on the investment for longer rotation quality sawlog regimes. Large-scale processing of plantation-grown eucalypts for solid-wood products is still at a preliminary stage (Malan, 2003, Nolan et al., 2005). Uncertainties of economic returns for growers of plantation sawlogs result from possible changes in; technology, site environment, pests and diseases, and the higher costs associated with a longer rotation. This means many growers are unwilling to undertake investment in large-scale plantation-grown eucalypts for sawlogs. Alternative pulpwood regimes are commonly seen as a lower-risk more attractive investment with a faster financial return (Kelly et al., 2005). The prospects for using clear wood at a later harvest-age, for high-quality solid timber and veneer applications are positive, but developers of breeding objectives for solid-wood or engineered wood product items from plantation grown timber must consider economic values and product marketability (Volker, 2007).

Wood quality issues in fast-grown plantation timber are a major concern to solid-wood and veneer processing industries. Wood characteristics that impact on solid-wood processing systems are less well understood than those of native forest eucalypt logs and the processed wood products will have to demonstrate their advantages over softwood products to compete in established markets (Nolan et al., 2005). One company, Forest Enterprises Australia Ltd., has already demonstrated the commercial use of new linear-flow multi-saw systems to utilise small-diameter *E. nitens* logs from short-rotation un-thinned and unpruned plantations (Cannon and Innes, 2007).

In recent years the majority of research on plantation grown eucalypts for solid-wood products has focused on improving silvicultural regimes and on aspects of timber processing, rather than improving the genetics of the plantation resource (Washusen and Innes, 2007). While there has been extensive research in softwood species on breeding objectives for solid-wood products, and studies into the genetics of associated traits (Ivkovic et al., 2006a, Ivkovic et al., 2006b), to-date there has been little similar research on eucalypt hardwoods (Raymond, 2002, Kube and Raymond, 2005, Hamilton et al., 2009b, Blackburn et al., 2010, Blackburn et al., 2011, Callister et al., 2011).

Research is now being undertaken on wood processing requirements and technologies for a range of products and one of the most powerful tools available to growers of plantations is the ability to improve the characteristics (traits) of a tree through selective breeding (Volker and Baker, 2007). Widespread research has been conducted on the genetic improvement of *E. nitens* for the pulp and paper industry (Hamilton et al., 2009b, Hamilton and Potts, 2008, Borralho et al., 1993, Greaves et al., 1997b, Stackpole et al., 2010). However, breeding objectives for solid and engineered wood products and the opportunities for their genetic improvement are less clear, particularly in the face of changing processing technologies and products (Raymond, 2002).

1.1 Aims of the thesis with reference to chapters

The thesis has the following principal aims:

- Establish a robust method of tracking selected tree identities in timber processing studies (Chapter 3).
- Assess the extent to which variation in stiffness and checking in sawn-boards of plantation-grown *E. nitens* is under genetic control and amenable to genetic improvement (Chapter 4).
- Examine the relationship between value-defining sawn-board traits and overall wood product recovery in a sawn-board *E. nitens* processing trial (Chapter 5).
- Assess the extent to which variation in chemical pulpwood traits and wood stiffness in rotary peeled veneer, and the relationships between them, are under genetic control and amenable to genetic improvement in plantation-grown *E. nitens* (Chapter 6).

Resources, wood properties and the products under study are presented in Chapter 2, while Chapter 7 provides a discussion, key findings and a conclusion.

2.0 CHAPTER 2. RESOURCES, WOOD PROPERTIES and PRODUCTS

2.1 Resources

The material used in all studies reported in this thesis was from an *E. nitens* base-population progeny trial established in 1993 near Tarraleah (latitude 42°18' S, longitude 146°27' E) in central Tasmania (Fig. 2.1). The trial site was 600 m above sea level with a mean annual rainfall of approximately 1 200 mm. Open-pollinated seed from 420 native-forest parent trees, sampled from twenty-eight localities extending over most of the natural range of *E. nitens* in the Central Highlands region of Victoria was used to establish seedlings for the trial. Genetically they encompassed three distinct races (Fig. 2.2): Southern, Northern and Connor's (Dutkowski et al., 2001, Hamilton et al., 2011), which were examined for genetic variation in each of the studies undertaken and reported in this thesis.

The trial used an Alpha design, a type of resolvable incomplete block design (Paterson and Williams, 1976). Within each of six replicates, 420 families were each represented by a single five-tree line plot, with replicates laid out in 21 incomplete blocks each containing 20 family plots. Spacing at planting was four metres between rows and two metres between trees within rows. Fertiliser (100 g of superphosphate and 125 g of 20:10:0 N:P:K) was applied to each tree three months after planting. No thinning or pruning was undertaken in the trial.

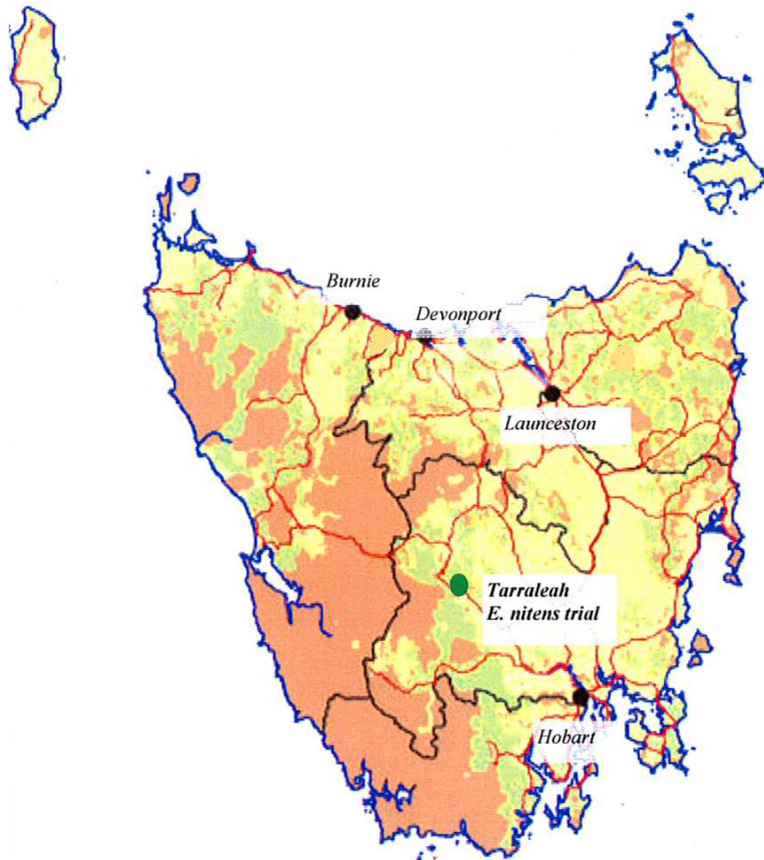


Figure 2.1 Map of Tasmania showing the Tarraleah *E. nitens* progeny trial location.

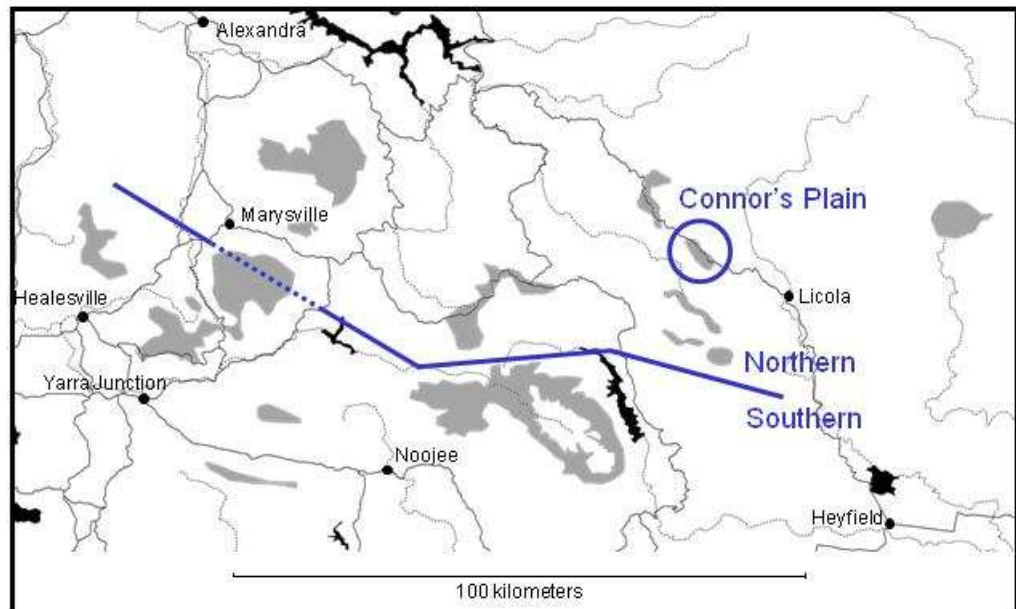


Figure 2.2 Geographical and genetically distinct localities of the Connor's Plain, Northern and Southern Central Victorian *E. nitens* races where trial seed material was selected from. Figure modified from Hamilton et al. (2008).

2.2 Wood Properties

2.2.1 *Tree Breeding for improved wood properties*

Tree growers and/or timber processors aim to improve the economic value of plantations on a per-hectare-per-year basis by setting economic breeding objectives. This is best achieved by defining bio-economic models, which relate production costs and financial returns to objective traits and appropriate economic weights can be applied to these different traits (Ponzoni and Newman, 1989, Shelbourne et al., 1997). Inevitably the objective will change with time to reflect factors such as; market requirements for the target product, changes in processing technology, environmental differences in plantation sites and local pest and disease problems (West, 2006). To accommodate these changes the breeding program must always have access to a range of tree genotypes to breed for new traits as circumstances demand (Burley, 2001).

Exactly which traits to include in a breeding objective for a target product should be based purely on economic grounds and account for all input and output costs for that product, rather than on the ease of measurement or how easily those traits are to change genetically (Ponzoni and Newman, 1989). However, Borralho et al. (1993) noted, when deciding which traits to include, tree breeders must consider how available the genetic and economic information will be. Whether or not it is possible to breed 'dual-purpose' trees producing both high quality pulp and high-value sawn timber will depend on inter-trait correlations (Bush, 2007). To-date production system modellers (Borralho et al., 1993, Greaves, 1997) and genetic improvement programs, for example, the work of the Southern Tree Breeding Association (STBA), have directed efforts towards maximising profitability for pulplog plantation investors and processors. Their objectives have been to improve profitability by minimising the cost of kraft-pulp production through weighting a combination of tree growth, density and pulp yield. However, tree breeders aiming to improve solid-wood products may need to select for different or additional traits (McKenzie et al., 2003b). In all breeding programs, careful

consideration must be given to inter-trait correlations. In the case of *Pinus radiata* breeding, for example, Gapare et al. (2006) reported that past selection for increased growth that had a negative correlation with density, has led to a timber of reduced wood density and strength.

Tree breeders wishing to produce high-value sawlogs for architectural and furniture products would need to include wood property traits related to sawn timber recovery, strength and final product appearance (Raymond, 2000). Until recently most research on plantation-grown eucalypts for solid-wood products has focussed on silviculture and timber processing issues rather than genetic improvement of the plantation resource (Washusen and Innes, 2007).

Plantation-grown *E. nitens* breeding objectives are well established for pulp-yield, but are yet to be determined for solid-wood or engineered-wood products. Which biological traits to be measured and their relationship with performance of the final processed product need careful consideration if maximum economic value and good product marketability are to be achieved. Pulplog plantation traits of interest will be those linked to woodchip and pulp-yield per hectare, while plantations aimed at growing quality sawlogs will wish to focus on traits linked to solid-wood properties, for example, sawn timber recovery, strength, dimensional stability and appearance (Bush, 2007). However, even when a modern sawmill achieves optimum sawn board recovery from a log, approximately half of the volume will be residual wood that can be utilised for alternative products. To-date these have mainly been paper products from pulped wood-chip. It is therefore likely that future breeding objectives for sawn-timber will also include traits favourable for pulp yield.

Tree breeders don't usually wait until sawlog harvest age before selecting and breeding. To reduce the generational interval for breeding and speed the capture of genetic gains (Cotterill and Dean, 1990, White et al., 2007,

Stackpole et al., 2010), they pick a set of selection criteria (e.g. density, basal area and stem straightness), which can be measured at a younger age.

2.2.2 Target breeding traits and selection criteria

Objective traits are traits (e.g. log volume per hectare at harvest) that tree growers and/or timber processors wish to improve in the final timber product, with the aim of increasing profitability of the production system. These improvements can be made by changing the silviculture regime, employing new or different production technology and/or breeding. To improve targeted objective traits by breeding; there should ideally be a minimal expression of genotype by environmental interaction, it should be relatively inexpensive to estimate the genotypic value of trees and it should be cheaper than, and/or more effective than applying different technology or modifying silviculture regimes (Hamilton, 2007a, Wu et al., 2007).

Selection criteria are used in breeding when objective traits cannot be assessed before harvest age as they may be difficult or expensive to measure and ideally have a high age-age correlation between a selection criterion and the objective trait or traits is known (White et al., 2007). An example would be, whole tree volume, where it is not necessary to wait until harvest as it would require felling the tree to make an accurate assessment and instead a selection criterion, diameter at breast height (DBH - usually 1.3 m in Australia) over bark is measured. Ideally selection criteria should be non-destructive to test, relatively cheap to assess and strongly genetically correlated with objective traits (Raymond and Apiolaza, 2004).

A more detailed discussion of objective traits and selection criteria used to improve economic returns for tree growers and sawn-board processors of *Eucalyptus nitens*, and the methodology used in trial assessment will be included within chapters three, four, five and six of this thesis. The following is an overview of the main traits under study in these chapters and the impact these have on the volume of product recovery and economic returns:

Growth is traditionally recognised as the most important trait. Improving productivity has been the main priority of *E. nitens* breeding programs for many years and this is reflected by the importance placed on growth in early genetic studies for this species (Pederick, 1979, King and Wilcox, 1988, Woolaston et al., 1991, Whiteman et al., 1992). The influence of this trait on plantation establishment costs, maintenance, harvest and transportation has been extensively researched (Namkoong et al., 1969, Porterfield, 1976, Cameron et al., 1989, Borralho et al., 1993, Greaves et al., 1997b, Chambers, 1999). As growth determines the rotation age of a plantation to reach the target log size for the production system and costs are compounded until harvest, then this trait has a major influence on profitability for tree growers. From an age of approximately four years plantation trees are measured for diameter at breast height at periodic intervals and the data is used to assess tree mortality and as selection criterion values to predict log volume at harvest age.

Survival in plantation stands means the number of trees per hectare that have survived to harvest (Chambers and Borralho, 1997), which determines the productivity and thereby the volume of timber recovered from a given area. In silvicultural regimes for sawlog production, plantation thinning must be taken into account.

Tree architecture traits include stem-straightness (stem-form or stem-sweep), stem-taper, forking and branching and are of more interest to sawlog plantation growers than pulplog growers. Stem-straightness is very important for high-value timber production, it impacts on profitability for tree growers and processors by influencing the length of usable log obtained from a tree, and the overall volume of sawn-board and/or veneered timber sheet recovered from that log. Straightness is usually defined as the maximum log deviation over a length of log in units of millimetres per meter (mm m^{-1}) (Chambers, 1999).

For selective tree breeding, Cotterill and Dean (1990) proposed a visual 6-point scoring scale method, which is used in many tree breeding programs. In this method the boundaries between scoring categories are set by the assessors for each trial site, such that there is an approximately normal distribution of individuals with a mean of 3.5, with categories 3 and 4 each containing about 33% of the individuals, categories 2 and 5, 15%, and categories 1 and 6, 2%. This scoring system has been shown to produce higher heritabilities, indicating good discrimination of stem straightness, when compared to alternatives such as 3-point and 9-point scoring scales (Raymond and Cotterill, 1990). However, this method cannot classify logs as suitable or unsuitable for sawn timber processing, because the straightness score that individual trees receive is determined in part by the site mean straightness: for example at a site with good overall straightness a tree scored as 4 might meet the minimum straightness criterion for sawing, whereas at a site where straightness was very poor, a tree scored as 5 may not. The main shortcoming of 'site-specific' methods is they do not allow direct comparison between sites or economic weights to be applied to different straightness categories, however they do enable an estimation of relative differences among genotypes in tree breeding programs.

Stem-taper is defined as the change in log-diameter per meter of log length and usually expressed in millimetres per metre (mm m^{-1}). For a given diameter at breast height, an increased log-taper reduces log volume and small-end diameter, in turn reducing the recovery of processed wood products (sawn-board or veneer) that can be obtained from processing. Good stem-form means straight circular logs with minimum taper, which results in the maximum recovery of high-quality timber and improved processing efficiency (Washusen and Clark, 2005).

Basic Density (commonly referred to as density) is the dry weight per unit of green volume, usually expressed as kilograms per cubic metre (kg m^{-3}). It is the complex ratio of earlywood to latewood, cell wall thickness, cell diameter and lignin content that determines the variation in basic density observed

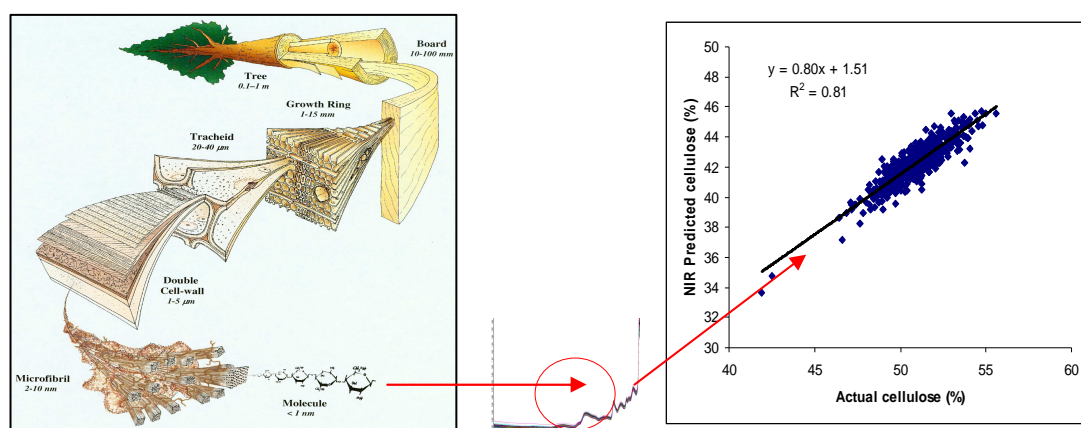
between different tree species and within a tree (King and Wilcox, 1988, Greaves et al., 1997b). These properties are a function of growth rate, climate, site, silviculture and genetics (Downes et al., 1997).

Density in trees has been reported to be under strong genetic control (Wang et al., 1984, Matheson and Raymond, 1986, Dean, 1990, Borralho et al., 1992, Eldridge et al., 1993, Kube, 2005, Hamilton, 2007b, Hamilton et al., 2009b, Stackpole et al., 2010) and is usually positively correlated with important pulp and sawn-board properties (Arbutnot, 1991, Borralho et al., 1993, Greaves et al., 1997b, Kube, 2005, Hamilton, 2007b, Stackpole et al., 2010). The method employed to assess basic density in studies conducted in this thesis was the accurate and precise direct water displacement technique (TAPPI, 1989).

Kraft-pulp yield (KPY) is a measure of the mass percentage of cell wall material remaining after pulping where the wood fibres have been separated from each other by the kraft process, the remaining product is a pulp containing almost pure cellulose fibres (Downes et al., 1997). The 'kraft' process is a chemical delignification procedure which uses the feedstock to produce wood pulp for high quality paper making, therefore the measurement of pulp-yield or potential pulp yield in a volume of wood is an important factor in the economics of pulping.

In recent years near-infra-red (NIR) spectroscopy (spectra generated when a wood sample is scanned with infra-red energy) has been used to predict KPY and cellulose content (CC) in ground woodmeal samples (Fig. 2.3). These are tested against KPY calibrations developed from independent samples from which the KPY and/or CC has been determined by laboratory chemical digestion (Downes et al., 2009). Chemical assays of wood samples to determine CC using the diglyme acid digestion methods established by Wallis et al. (1997) have proved a reliable analytical technique, with correlations of CC and predicted KPY being as high as 0.93, Wallis et al. (1997) reported in Downes et al. (1997). Recent research on the application

of NIR for the prediction of wood properties has demonstrated the technology can be used to predict cellulose content and thereby kraft pulp yield, from analysis of the generated spectra (Fig. 2.3) (Downes et al., 2007, Schimleck, 2007, Wimmer et al., 2008). Its use offers numerous advantages being cheap, rapid with easy sample preparation and non-destructive. Many samples can be cost effectively analysed, which makes it ideal for use in breeding programs. The resulting spectra can be compared to multi-site and/or multi-species spectral database models (Schimleck, 2007, Downes et al., 2009, Downes, 2011), or an independent calibration model for the tool can be developed from a sub-sample of results obtained using the diglyme method (Wallis et al., 1997), which can then be used to predict the cellulose content and kraft pulp yield of the remaining sample set.



Jonathon Harrington, SCION

Figure 2.3 NIR prediction of cellulose content. Graphs above were captured from trial assessments using OPUS 5.5 (Bruker, 2005).

Physical properties can substantially reduce or improve the yield of appearance-grade sawn timber recovered from plantations (Washusen et al., 2009, Lausberg et al., 1995, McKenzie et al., 2003b, McKimm, 1985, Shelbourne et al., 2002). One such property having a major influence on the yield in *E. nitens* is checking, which refers to radially distributed cracks (checks) observed in timber. A distinction is usually made between exposed surface checks, observed on the tangential and radial faces of boards, and internal checks (Fig. 2.4), but both may originate from differential shrinkage when the wood dries (Blakemore and Northway, 2009). Checking decreases

grade recovery and therefore the economic value of plantation-grown *E. nitens*. Most eucalypts have a strong tendency to check on the wide faces of back-sawn boards (Blakemore and Langrish, 2008, Valencia Baier, 2008) and the incidence of both surface and internal checking increases with collapse (Hamilton, 2007a, Hamilton et al., 2009a). Washusen (2011) notes, when check-prone eucalypts species such as *E. nitens* are established to produce appearance sawn-timber, financial pressure to produce shorter rotation smaller sawlogs that will be back-sawn to increase board volume recovery, rather than longer rotation larger logs that can be quarter-sawn, may result in an increase in checking and therefore a reduced product value per log. Other physical properties impacting on the yield of sawn boards (but not under study in this thesis) are: knots, resin canals, wandering pith, insect attack, stem defects, decay and discolouration.

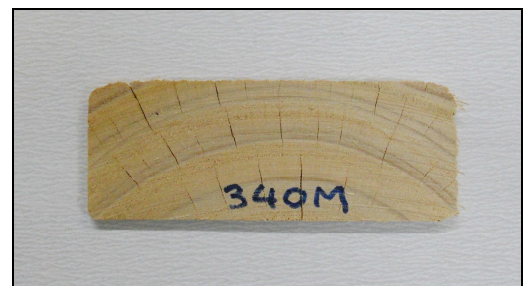


Figure 2.4 Checking expressed radially by differential shrinkage in wood disks (above upper), on a machined board surface (left) and internally in a wafer extracted from the machined board (right).

Wood stiffness and strength and longitudinal growth stress are important measures of the suitability of structural timber in the construction industry (Nolan et al., 2005, Standards Australia, 2000, Standards Australia, 1997). Timber stiffness - static modulus of elasticity (MOE_{static}), indicates the extent to which a sawn-board will deflect under load (Fig. 2.5) and studies have shown that the velocity of an acoustic wave signal passing through wood in standing trees or logs is positively correlated with sawn-board static MOE in *E. nitens* (Farrell et al., 2008). Acoustic wave velocity is easily measured by readily available equipment, which allows a large number of trees, logs or boards to be assessed per day.

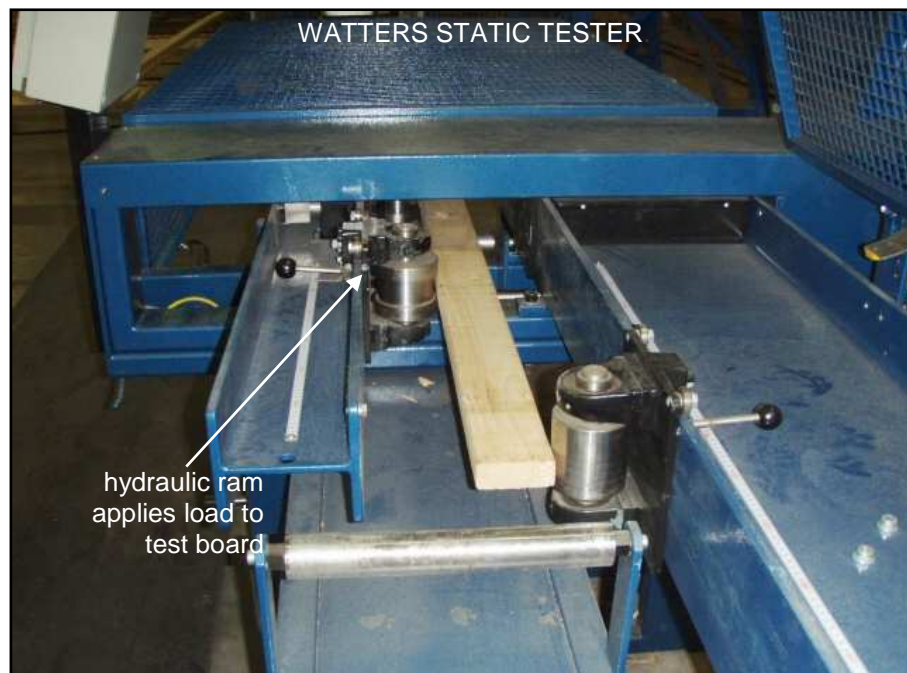


Figure 2.5 Machined board under an applied load for static MOE testing.

During sawing there may be constraints on the application of sawing strategies as a consequence of high levels of growth stresses, which often result in downgrading of logs due to end-splitting (Fig. 2.6), increased processing costs and a reduction in sawmill economic performance. High growth stresses can also contribute to flitch and board deflection (spring, bow and cupping due to stress re-balance), board width and thickness variation, and increase the incidence of board end-splits (Washusen et al., 2007).

These negative wood attributes may reduce volume recovery and product value through material loss from board end-docking, reduced sawn-board length and width and from product downgrade (Washusen and Innes, 2007).



Figure 2.6 Log-end splitting in *E. Nitens*.

Engineered wood products such as plywood and laminated veneer lumber are certified by the Accreditation System of Australia and New Zealand (JAS-ANZ) and by Engineered Wood Products Association of Australia (EWPA). Non-structural panels are certified by the EWPA only. Each certified product is manufactured with specific veneer arrangements and characteristics to provide optimal performance in their intended application (EWPA, 2008). The following desired characteristics show that a tree's wood property traits would have a major bearing on the final quality and strength of peeled veneer and, in-turn, performance of the final engineered wood product:

- Density and strength of the individual veneer, as usually the higher the density more superior the engineering qualities. Generally due to lower levels of imperfections the higher the appearance grade the higher the stress grade, although high-quality face veneers are usually specified for aesthetic reasons.
- Thickness and arrangement of the veneers, which determines the dimensional stability. The cross lamination of veneer sheets results in

products that are more stable under moisture content and temperature changes than solid-wood products.

- **Strength and stiffness**, as the outer veneers have the greatest influence on strength and stiffness; increasing face-sheet thickness will increase the plywood's strength and stiffness in the face grain direction, whereas thin face veneers with thicker underlying cross band veneers will tend to give the plywood more equal strength and stiffness characteristics in both directions. Laminated veneer lumber has only unidirectional veneers laid parallel to beam length, which optimizes its performance as a beam span in one direction.

2.3 Products

Presently logs not meeting sawlog categories for higher-value defect-free appearance grade products, can be processed into woodchips for pulpwood, structural sawn timber or into rotary peeled veneer sheets that are used to manufacture plywood products and laminated veneer lumber (Forestry Tasmania, 2007). For the foreseeable future a percentage of any plantation stand will be processed to woodchips for the pulpwood industry (McKenzie et al., 2003a).

2.3.1 *Eucalyptus nitens* sawn board products

The machined sawn-board product from trees examined in the 'stiffness and checking' (Chapter 4) and the 'sawn-board recovery' study (Chapter 5) has been marketed in Australia as EcoAsh[®], which is used mainly for framing studs, joists, bearers, and roof and floor trusses in housing construction. In this timber the number of grade defects such as checking, kino and knots usually prevents its acceptance as a higher-value appearance grade product. Compared with structural pine of similar dimension, EcoAsh[®] has greater strength and nail-holding capacity. These improved engineering outcomes have resulted in the brand being distributed for sale through hardware outlets (Cannon and Innes, 2007). With a product proven for strength and provided market returns are favourable, *E. nitens* could be grown under longer

rotations and silviculture regimes involving pruning and thinning, to produce select – AS 2796.3 (Standards Australia, 1999) and standard grade – AS 2796.2 (Standards Australia, 2006) timber, for the appearance grade market for products such as furniture and mouldings. The aim would be to produce higher quality sawn timber products free of the undesirable features typical found in timber milled from smaller diameter logs from short-rotation pulpwood plantations with no pruning or thinning.

2.3.2 *Eucalyptus nitens* engineered wood products

The engineered wood products industry purchases hardwood and softwood logs for rotary peel veneering, or purchases mill byproducts such as sawn off-cuts or woodchips and processes them into products such as plywood, veneer, laminated veneer lumber, and fabricated building products (ABARE, 2007). These are sold to construction companies, building contractors, structural component manufacturers, furniture makers and to export markets. The bulk of engineered wood products produced in Australia are panel products such as plywood, particle board and medium density fibreboard (IBISWorld, 2010a). There is now a growing market for load bearing products including, laminated veneer lumber and plywood I-beams (I-joists) that can provide a lightweight alternative to steel. In Australia, laminated veneer lumber and I-joists have captured some of the flooring, roof and wall framing markets.

In the pulpwood and veneer study (Chapter 6) the product under study was a rotary peeled veneer sheet. Sliced veneers are used for different tree species and end products, but rotary peeled sheets are used in engineered wood products, where the peeled veneer sheets are glue-laminated into plywood or laminated veneer lumber. For a given timber resource, engineered wood products have a greater strength and uniformity than sawn timber of the same dimensions and may be used over a wider range of applications. Compared with steel, engineered wood products can offer a lower cost solution to the increasing demand for high performance building components (EWPAA, 2008). These products often appeal to customers who want

‘carbon friendly’ alternatives to concrete and steel, but are concerned about the environmental impact of using native forest timbers (McGavin, 2009).

In Tasmania a private company (Ta Ann Tasmania Pty Ltd) has operated two rotary peeled veneer mills which process billets extracted from native forest eucalypt logs. These mills have been used to conduct research trials of billets from plantation-grown *E. nitens* trees.



Figure 2.7 Typical use of *E. nitens* solid wood products manufactured from sawn-board and veneer sheet, examined in studies undertaken during this thesis.

2.3.3 *Eucalyptus nitens* pulpwood products

Eucalyptus is the most widely used hardwood fibre for papermaking in the world, the shorter fibres with thin fibre walls result in a large number of fibres per unit volume of pulp, which produces a smooth opaque matrix (Clarke et al., 2008). *Eucalyptus globulus* is recognised as having superior wood properties for kraft pulping (Beadle et al., 1996), but *E. nitens* will be preferred on many sites due to its cold tolerance and *Mycosphaella* resistance and the fibre qualities of *E. nitens* are still considered suitable for

the production of higher quality and speciality paper (Cotterill and Macrae, 1997, Kibblewhite et al., 1998, Clarke, 2000).

In the past five years the Australian paper industry has struggled to maintain its market share due to greater import competition (IBIS*World*, 2010b). To remain competitive in the industry companies must aim to reduce kraft processing costs while increasing the amount of kraft pulp yield per volume of wood processed (Greaves et al., 1997b). Increasing KPY improves the economics of processing by reducing production costs per volume of wood processed and by increasing the pulp mills production capacity (Downes et al., 1997, Greaves, 1997).

The 'peeled veneer' study (Chapter 6) was conducted, in-part, to meet the requirements of a Forest & Wood Products Australia project (Project number: PNB139-0809) aiming to identify the genetic parameters that affect the quality of rotary peeled veneer. Given that pulpwood will be a by-product of trees grown for solid wood products, the project examined the compatibility of simultaneously breeding for the objective traits of both products, where wood stiffness was identified as the target trait in the final solid wood product, the rotary peeled veneer sheet.

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CHAPTER 3. IMPROVED METHODS FOR ACHIEVING
TRACEABILITY OF TREE AND LOG IDENTITIES IN TIMBER
PROCESSING STUDIES

4.0 CHAPTER 4. STIFFNESS AND CHECKING OF *EUCALYPTUS NITENS* SAWN BOARDS: GENETIC VARIATION AND POTENTIAL FOR GENETIC IMPROVEMENT

4.1 Introduction

While most industrial plantations of eucalypts are grown for pulp and paper production, there is increasing interest in utilising plantation-grown eucalypts for the production of solid-wood products (Nolan et al., 2005, INFOR, 2004). However, until recently most research on plantation-grown eucalypts for solid-wood products has focused on silviculture and timber processing issues rather than genetic improvement of the plantation resource (Washusen and Innes, 2007). While there is an extensive background of research for softwood species on the breeding objectives for solid-wood products, and the genetics of associated traits (Ivkovic et al., 2006a), there are few such studies for eucalypts (Hamilton and Potts, 2008, Hamilton et al., 2009b, Raymond, 2002).

Eucalyptus nitens Maiden is an important hardwood plantation species in temperate regions of the world (Hamilton et al., 2008, INFOR, 2004, Pallett and Sale, 2004). Most *E. nitens* breeding programs have focused on selecting traits for kraft pulpwood production including increased volume production, higher basic density and higher pulp yield (Hamilton et al., 2008, INFOR, 2004, Greaves et al., 1997b, Borralho et al., 1993). However, breeders aiming to improve structural timber products may need to select for different or additional traits (McKenzie et al., 2003a).

Sawmilling and processing studies on *E. nitens* have indicated that, as well as knots, defects induced from timber drying can substantially reduce the yield of appearance-grade sawn timber recovered from plantations (Washusen et al., 2009, Lausberg et al., 1995, McKimm, 1985, Shelbourne et al., 2002). Drying defects include cupping, surface checking, internal checking and splitting. Checking refers to radially distributed cracks (checks)

observed in timber. A distinction is usually made between exposed surface checks, observed on the tangential and radial faces of boards, and internal checks, observed on board ends. However, after moulding or planing, internal checks can be exposed as open cracks or raised grain on board faces. The exposure of internal checks in late stages of timber processing is a common cause for complaint and rejection of eucalypt timber by customers (Taylor et al., 2003). Check-inducing drying stresses can develop in a board as a result of variation in collapse between latewood and earlywood (Chafe et al., 1992), shrinkage anisotropy (Svensson and Martensson, 1999), variation in shrinkage between sapwood and heartwood (Lausberg et al., 1995), the presence of defects such as knots, and moisture gradients within boards during drying (Taylor et al., 2003, Nolan et al., 2005).

Along with timber defects, such as knots, and timber strength (modulus of rupture, MOR), timber stiffness is an important measure of the suitability of structural timber for the construction industry (Nolan et al., 2005, Standards Australia, 2000, Standards Australia, 1997). Timber stiffness indicates the extent to which a board will bend under load and is measured by its static modulus of elasticity (MOE) (AS 2082, 2000; AS/NZS 1748, 1997). However, it has been shown that acoustic wave velocity (AWV) through timber in standing trees, logs or sawn boards is positively correlated with board static MOE in *E. nitens* (Farrell et al., 2008) and a number of other tree species (Carter et al., 2006, Dickson et al., 2003, Dickson et al., 2004, Farrell et al., 2008, Hamilton et al., 2008). AWV can be measured quickly using commercially-available tools, allowing a large number of trees, logs or boards to be assessed per day. However, before standing-tree AWV can be adopted as a selection trait to improve stiffness in *E. nitens* breeding programs, knowledge of genetic variation in AWV and board static MOE, and the strength of genetic correlations between these traits, is required.

The aim of this study was to estimate heritabilities and determine the strength of genetic correlations among AWV, stiffness and checking traits and examine their implications for genetic improvement of stiffness and checking

through selective breeding. A further aim of the study was to assess the possible effect of past breeding for higher basic density in pulpwood breeding programs on these traits.

4.2 Materials and methods

4.2.1 Progeny trial

The Tarraleah *Eucalyptus nitens* progeny trial was established in 1993 by Norske Skog Paper Mills (Australia) Pty. Ltd., on an ex-pine (*Pinus radiata* D. Don) plantation site 600 m above sea level with a mean annual rainfall of approximately 1 200 mm (Hamilton et al., 2009b). The trial was established using open-pollinated seed from 422 native-forest parent trees sampled from 28 localities and three races: ‘Southern’, ‘Northern’ and ‘Connor’s Plain’ (Dutkowski et al., 2001, Hamilton et al., 2011). The localities extended over most of the natural range of *E. nitens* in the central highlands region of Victoria, Australia. The trial was an incomplete block design comprising six replicates of 21 incomplete blocks, each containing 20 five-tree row plots of open-pollinated families. Initial espacement was 4 m between rows and 2 m between trees within rows. No thinning or pruning was undertaken in the trial. At age 13 years, one year prior to the felling of trees for this study, all candidate trees in three trial replicates were measured for diameter at breast height and assessed for stem straightness according to a six-point subjective scale (Cotterill and Dean, 1990). At the time of this assessment, approximately 86% of planted trees were surviving.

4.2.2 Tree selection and processing

For the study of wood properties, a total of 560 trees from 129 families were selected for milling. For sawmill processing selected trees had to meet a minimum size criterion (150 mm small end diameter under bark) and have acceptable log straightness, as indicated by their stem straightness score. The aim was to process at least four trees per family to enable estimation of genetic parameters of product traits and associated potential selection traits.

As far as possible, selected trees from each family were chosen such that all three harvested replicates were represented.

Selected trees were felled and a 5.6 m butt log was extracted from each. Average stump height was 0.25 m. To reduce the incidence of log-end spitting after tree felling and de-barking, exposed log-end surfaces were 'gang-nailed' and coated with log grease.

At the sawmill, logs were placed on bolsters, and disks approximately 75 mm thick were cut from the top and bottom of each log. Optical scanning indicated that 64 logs exhibited excessive sweep and these logs were not accepted for sawmilling. The remaining logs were sawn with a R200 HewSawTM. The R200 HewSaw chips, saws and edges small-diameter logs in a single pass (Cannon and Innes, 2007). Logs were batched into five size classes based on their small-end diameter, and for each diameter class one of five cutting patterns was used to produce two, three, four, or six boards per log. Green-sawn boards were stacked in racks for air-drying over a seven-month period. When moisture content had fallen below an average of 20%, boards were steam reconditioned and kiln-dried, after which they were planed to final product dimensions. Two diametrically opposite outer 90 x 35 mm back-sawn boards from each tree were utilised for further study.

Individual tree identities were maintained during harvesting and log transport to the sawmill using numbered wooden identification plugs glued into a 38 mm hole drilled to a depth of 40 mm below the cambium of standing trees, at a height of approximately 0.4 m above ground. The tree was marked with a painted white band just below this hole, to enable the felling contractor to accurately position the cutting head of the harvester. This under-bark identification-plug method is considered unique to this study. Paper log-end templates, adapted from those developed in previous studies (Smith et al., 2003), were glued to both ends of each at the time of top and bottom disk removal to maintain tree identities of boards during sawing and drying. The tree identity code, with a suffix indicating the log end ('U' for upper and 'L' for

lower), was printed many times on each log end template, ensuring that tree identity and board orientation were maintained throughout sawing and board processing.

4.2.3 Assessment of acoustic wave velocity and stiffness

A FAKOPPTM microsecond (single pass) timer was used to measure the ‘time-of-flight’ of a stress wave between two probes located 0.5 m and 1.7 m from the base of each tree on the tree’s southern side, from which standing-tree AWV was calculated from the stress-wave flight time and known distance. To obtain repeatable measurements, the frequency of strikes and the impact strength of each strike to the transmitting probe was, as much as possible, maintained within and among trees.

At the sawmill, log lengths were measured and a DIRECTOR HM200TM ‘Hitman’ instrument was used to assess log AWV. The large end of each log was repeatedly struck until the three measurements required by the Hitman instrument to calculate AWV had been recorded.

After sawmilling, the static MOE of a 1.8 m board section, cut from the upper end of one outer board from each tree was randomly selected for assessment (Standards Australia, 1992). The measurements were performed using a Watters static MOE tester loaded in a four-point configuration.

4.2.4 Assessment of basic density and checking

After extraction from log ends, disks were double-wrapped in plastic and stored in a cold room at 2°C to reduce moisture loss. Within two weeks, the disk from the upper end of each log (i.e. adjacent to the 1.8 m board section used to assess MOE) was band-sawn to extract two pith-to-bark wedge sectors of approximately 30 degrees (Fig. 4.1). One wedge from each tree was used to determine basic density using the water displacement method (TAPPI, 1989). The remaining wedge from each tree was air-dried at 30°C and then stabilised to equilibrium moisture content (approximately 12%) in a controlled-humidity environment. This set of air-dried wedges was then

visually assessed for the occurrence of internal checks on a scale from one (infrequent or not visible) to six (frequent and highly visible). To maintain consistency of scoring, a reference set of wedges was continually referred to during assessment (Fig. 4.1).

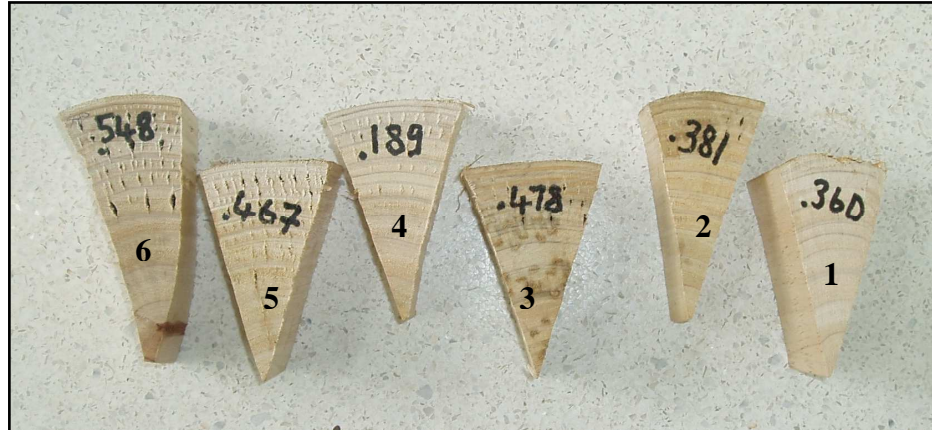


Figure 4.1 Reference wedges used for the visual assessment of internal check wedge scoring.

To assess internal checking in boards, cross-section ‘wafers’ approximately 1.5 mm thick were extracted from the randomly selected outer board at points representing tree heights of approximately 0.7 m, 3.6 m and 5.6 m above the ground. Steam reconditioning during board processing meant that open checks commonly seen at the air-dried stage had largely closed and, thus, it was not possible to assess checking using image analysis (Blakemore and Langrish, 2008). However, internal checking was still expressed as visible fissures in board wafers, often extending radially through one or more growth rings, and was assessed using a one (infrequent or not visible) to six (frequent and highly visible) subjective score. Each wafer was examined against the light, to help distinguish between true internal checks and surface checks. To maintain consistency of scoring, a reference set of wafers was continually referred to during assessment. Scores from the three wafers per board were averaged prior to analysis.

Board surface checks that could be detected visually at a distance of 1 m were assessed on the alternate outer board per tree on the outer (cambial)

surface only, as the expression of checking was observed to be far greater on this surface than on the pith surface, possibly due to tangential/radial shrinkage anisotropy (Svensson and Martensson, 1999). The number of checks and their total length in each board was recorded.

4.2.5 Statistical Analyses

The following mixed linear model was fitted to the data in ASReml (Gilmour et al., 2006) to perform univariate restricted maximum likelihood analyses:

$$Y = \text{MEAN} + \text{REP} + \text{RACE} + \text{FAMILY}(\text{RACE}) + \text{RESIDUAL} \quad (4.1)$$

where; Y is a vector of trait observations, MEAN is the mean value, REP are the replicate effects fitted as a fixed factor, RACE are the race effects fitted as a fixed factor, $\text{FAMILY}(\text{RACE})$ are the family within race effects fitted as a random factor and RESIDUAL is a vector of residuals. As the selected trees were only a small subset of the entire trial, terms for incomplete blocks and plots were omitted from the model. Individual race and overall means were calculated for each trait. The significance of the RACE term for each trait was gauged with a Walds F-test, where $\text{FAMILY}(\text{RACE})$ was the error term and the denominator degrees of freedom were computed using the numerical derivatives algorithmic method (Gilmour et al., 2006).

The additive variance (σ_{add}^2), phenotypic variance (σ_{pheno}^2) and open-pollinated narrow-sense heritability (h_{op}^2) were estimated for each trait as follows:

$$\hat{\sigma}_{\text{add}}^2 = \frac{\hat{\sigma}_{\text{fam}}^2}{r} \quad (4.2)$$

$$\hat{\sigma}_{\text{pheno}}^2 = \hat{\sigma}_{\text{fam}}^2 + \hat{\sigma}_{\text{residual}}^2 \quad (4.3)$$

$$\hat{h}_{\text{op}}^2 = \frac{\hat{\sigma}_{\text{add}}^2}{\hat{\sigma}_{\text{pheno}}^2} \quad (4.4)$$

where σ_{fam}^2 and $\sigma_{\text{residual}}^2$ are the variance components for *FAMILY(RACE)* and *RESIDUAL* respectively and r is the coefficient of relationship, which was taken to equal 0.4 to account for the levels of selfing and relative matings that typically occur in open-pollinated eucalypt progenies (Griffin and Cotterill, 1988). The coefficient of additive genetic variation (CV_{add}) was calculated as the square root of the additive genetic variance expressed as a percentage of the overall trait mean. The significance of the family variance, and therefore the significance of the additive variance, for each trait was tested using a ‘one-tailed’ likelihood ratio test (Gilmour et al., 2006).

A bivariate model, which extended the univariate model, was used to estimate pair-wise covariances among families and residuals. Additive genetic correlations (r_g) were estimated according to the following function:

$$r_{g_{12}} = r_{fam_{12}} = \frac{\hat{\sigma}_{fam_{12}}}{\sqrt{\hat{\sigma}_{fam_1}^2 \hat{\sigma}_{fam_2}^2}} \quad (4.5)$$

where $r_{fam_{12}}$ is the *FAMILY(RACE)* correlation between traits 1 and 2, $\hat{\sigma}_{fam_{12}}$ is the *FAMILY(RACE)* covariance component between traits 1 and 2 and $\hat{\sigma}_{fam_1}^2$ and $\hat{\sigma}_{fam_2}^2$ are the *FAMILY(RACE)* variances for traits 1 and 2 respectively.

Significance tests of inter-trait genetic correlations against zero were conducted using ‘two-tailed’ likelihood ratio tests and against one or minus one, as appropriate, using ‘one-tailed’ likelihood ratio tests (Gilmour et al., 2006). Inter-trait Pearson’s correlation coefficients among phenotypic observations were also calculated.

4.3 Results and discussion

Significant differences among the *E. nitens* races were observed in all ‘stiffness traits’ (i.e. standing-tree AWV, log AWV and board static MOE), while race differences in basic density and checking traits were not significant (Table 4.1). The Southern race had the highest mean values for stiffness

traits. Likelihood ratio tests showed highly significant ($P < 0.01$ or $P < 0.001$) additive genetic variance for wedge basic density, standing-tree AWW, log AWW, board static MOE, board wafer internal check score and board surface check count. Remaining traits (wedge internal check score and board surface check length) also exhibited significant ($P < 0.05$) levels of additive genetic variance. Estimated heritabilities varied widely from 0.25 for board surface check length to 0.85 for standing-tree AWW.

Estimated additive genetic correlations between AWW (both standing-tree and log) and board MOE were strongly positive (r_g ranging from 0.92 to 1.05) and significantly different from zero (Table 4.2) but not from +1. Furthermore, strongly positive genetic correlations, which were significantly different from both zero and one, were estimated between wedge basic density and all stiffness traits. Estimated genetic correlations between the internal checking traits of wedge score and board wafer score and between the board surface checking traits of count and length were both strongly positive. These correlations were significantly different from zero but not from one. Estimated genetic correlations between board wafer internal check score and both board surface checking traits were moderate and significantly different from zero but not one. However, estimated genetic correlations between wedge internal check score and board surface checking traits were not significantly different from zero. A strongly positive (adverse) genetic correlation was estimated between wedge basic density and board surface check length but other correlations between basic density and checking traits were not significantly different from zero. Genetic and phenotypic correlations between stiffness and internal checking traits were generally weakly negative, whereas those between stiffness and board surface checking traits were, in the main, weakly to moderately positive. However, of the genetic correlation estimates between stiffness and checking traits, only that between log AWW and board wafer internal check score and that between standing-tree AWW and board surface check length were significantly different from zero.

Table 4.1 Estimated Race means, F-ratio of difference among races, overall mean, additive variance, narrow-sense heritability (h_{op}^2) and coefficient of additive variation (CV_{add}) for each trait.

Trait	Race mean (SE)			Race F-ratio	Overall mean (SE)	Additive Variance (SE)	h_{op}^2 (SE)	CV_{add} (%)
	Southern	Northern	Connor's Plain					
Wedge basic density (kg m ⁻³)	478 (2)	477 (5)	479 (9)	0.06 ^{ns}	478 (4)	513 (149)***	0.41 (0.11)	4.7
Standing-tree acoustic wave velocity (km s ⁻¹)	3.36 (0.01)	3.23 (0.03)	3.18 (0.05)	12.95 ***	3.26 (0.02)	0.028 (0.005)***	0.85 (0.12)	5.1
Log acoustic wave velocity (km s ⁻¹)	3.61 (0.01)	3.52 (0.03)	3.51 (0.06)	5.04 **	3.55 (0.02)	0.027 (0.006)***	0.71 (0.12)	4.7
Board static modulus of elasticity (GPa)	10.9 (0.1)	10.8 (0.2)	9.6 (0.4)	5.45 **	10.4 (0.2)	0.744 (0.287)**	0.37 (0.13)	8.3
Wedge internal check score	2.46 (0.06)	2.72 (0.14)	2.13 (0.27)	2.26 ^{ns}	2.44 (0.1)	0.248 (0.13)*	0.20 (0.10)	20.4
Board wafer internal check score	2.58 (0.05)	2.45 (0.11)	2.48 (0.21)	0.62 ^{ns}	2.5 (0.08)	0.311 (0.084)***	0.52 (0.12)	22.3
Board surface check count	41.4 (1.4)	42.2 (3.2)	35.8 (5.9)	0.47 ^{ns}	39.8 (2.3)	129 (65)*	0.25 (0.12)	28.5
Board surface check length (m)	3.17 (0.11)	3.27 (0.26)	2.91 (0.49)	0.21 ^{ns}	3.12 (0.19)	0.943 (0.436)**	0.27 (0.12)	31.1

^{ns} Not significant, * P<0.05, ** P<0.01, *** P<0.001

Table 4.2 Inter-trait genetic (below diagonal) and phenotypic (above diagonal) correlations with standard errors shown in parentheses

	Wedge basic density	Standing-tree acoustic wave velocity	Log acoustic wave velocity	Board static modulus of elasticity	Wedge internal check score	Board wafer internal check score	Board surface check count	Board surface check length
Wedge basic density		0.29 (0.04) ***	0.24 (0.04) ***	0.18 (0.05) ***	-0.15 (0.04) ***	-0.08 (0.05) ns	0.03 (0.05) ns	0.07 (0.05) ns
Standing-tree acoustic wave velocity	0.60 (0.13) ***		0.67 (0.03) ***	0.47 (0.04) ***	-0.06 (0.04) ns	0.01 (0.05) ns	0.1 (0.05) *	0.14 (0.05) **
Log acoustic wave velocity	0.67 (0.14) ***	0.92 (0.05) ***		0.47 (0.04) ***	-0.18 (0.04) ***	-0.04 (0.05) ns	0.06 (0.05) ns	0.08 (0.05) ns
Board static modulus of elasticity	0.62 (0.21) ***	1.05 (0.19) ***	0.98 (0.13) ***		-0.07 (0.05) ns	0.12 (0.05) *	0.19 (0.05) ***	0.22 (0.05) ***
Wedge internal check score	-0.22 (0.27) ns	0.11 (0.22) ns	-0.22 (0.22) ns	0.01 (0.32) ns		0.31 (0.05) ***	0.2 (0.05) ***	0.09 (0.05) ns
Board wafer internal check score	-0.03 (0.20) ns	-0.08 (0.16) ns	-0.31 (0.16) *	-0.12 (0.23) ns	1.10 (0.24) ***		0.21 (0.05) ***	0.23 (0.05) ***
Board surface check count	0.23 (0.27) ns	0.36 (0.21) ns	-0.05 (0.23) ns	0.44 (0.29) ns	0.51 (0.33) ns	0.52 (0.24) *		0.82 (0.03) ***
Board surface check length	0.61 (0.26) *	0.46 (0.20) *	0.21 (0.21) ns	0.49 (0.28) ns	0.48 (0.34) ns	0.49 (0.22) *	0.91 (0.09) ***	

^{ns} Not significantly different from zero, * P<0.05, ** P<0.01, *** P<0.001

4.3.1 Basic density

Increased whole-tree basic density is a breeding objective trait in many *E. nitens* kraft pulpwood breeding programs (Hamilton et al., 2008, INFOR, 2004). Although assessed on disk wedges extracted at approximately 6 m, in contrast to the more commonly assessed wood cores at 0.9 to 1.3 m, the estimated heritability (0.41) and relatively low estimated coefficient of additive genetic variation (5%) observed in basic density were consistent with previous estimates of these parameters in *E. nitens* (Hamilton et al., 2008, Hamilton and Potts, 2008). Estimated heritability of basic density in this *E. nitens* trial, determined from wood cores sampled at a height of 0.9 m at age 9 years, was very similar at 0.42 (Hamilton et al., 2009a, Hamilton et al., 2009b), and the estimated additive genetic correlation between wedge and core assessments, based on 29 families in common between the two studies, was 1.18 (SE 0.29).

4.3.2 Acoustic wave velocity and stiffness

Acoustic wave velocity (AWV) was assessed on standing trees and in logs to assess its effectiveness as an indirect measure of board static MOE. The southern race, which exhibited the highest AWVs and MOE in this study, has previously been identified as being superior to other central Victorian races for a number of kraft pulpwood and solid-wood traits (Hamilton et al., 2009b). Furthermore, the significant additive variance, and relatively high heritability (0.37) and coefficient of additive genetic variation (8%) for board static MOE indicated that *E. nitens* board stiffness could be improved relatively rapidly through selective breeding. The coefficient of additive genetic variation for this trait was particularly high compared with other wood property traits (Hamilton et al., 2008). The heritabilities for both standing-tree and log AWV were also notably high (0.85 and 0.71 respectively). Publicly-available estimates of heritability for these traits in other eucalypt species are, in a number of cases, also high for example *E. pilularis*, 0.63 and 0.19 respectively, and *E. dunnii*, 0.42 and 0.92 respectively (Raymond et al., 2008).

The extremely strong and highly significant genetic correlation between standing-tree AWW and board static MOE ($r_g = 1.05$) strongly supports the use of standing-tree AWW as a selection trait in eucalypt tree breeding programs aiming to improve timber stiffness. However, it is likely that the strength of this relationship would be weaker between selection-age (about 6-8 years) standing-tree AWW and rotation-age at about 10-12 years (Cannon and Innes, 2007), for structural timber board static MOE, due to imperfect age-age genetic correlation. Genetic correlations between standing-tree AWW and board static MOE in eucalypts have not been published previously. However, Valencia (2008) found that standing-tree AWW explained a significant level of variation in static MOE of sawn boards in a study of 22-year-old *E. nitens*, and Dickson et al. (2003) found a strong and significant phenotypic relationship between these traits in 9-year-old (0.64), but not in 25-year-old (0.07), *E. dunnii*. Furthermore, the moderate phenotypic correlation (0.47) between log AWW and board static MOE observed in this study supported the findings of other studies on *E. nitens* in Tasmania that have shown that the phenotypic correlations between log AWW and static MOE is sufficiently strong at 0.51 for trees between 13-15 years of age and 0.18 for trees 8 years of age (Farrell et al., 2008) to allow the segregation of logs into wood stiffness classes prior to processing.

Wood density is generally positively associated with MOE (Dickson et al., 2003, Nolan et al., 2005) and the strongly positive genetic correlation (0.62) between wedge basic density and board static MOE observed in this study further indicates that selection for basic density, such as that which has taken place in many pulpwood breeding programs, would result in a favourable correlated response in static MOE. However, the strength of this correlation was not nearly as great as that between standing-tree AWW and MOE, indicating that AWW assessment of progeny trials, additional to or instead of basic density, would result in greater genetic gains in static MOE.

4.3.3 Checking

Eucalyptus nitens sawmilling and processing studies have indicated that drying defects, such as checking, can substantially reduce the recovery of appearance-grade sawn timber (Haslett, 1988, Lausberg et al., 1995, McKenzie et al., 2003a, McKenzie et al., 2003b, Reid and Washusen, 2001, Valencia Baier, 2008, Washusen et al., 2009). This study provides the first quantitative estimates of genetic control of checking in eucalypts.

Encouragingly, the significant additive genetic variances, moderate to high heritabilities (0.20 - 0.52) and high coefficients of additive variance (20 - 31%) observed for checking traits in this study indicate that checking could be reduced through selective breeding. However, the strength of the genetic correlation between internal and surface checking and the strength and direction of the genetic correlations of checking traits with basic density and AWV remain unclear. Because of the low phenotypic correlations involved (Table 4.2), neither basic density nor AWV can be recommended as reliable predictors of checking in boards.

The strongly positive genetic correlations observed between the internal checking traits of wedge score and board wafer score and between the board surface checking traits of count and length indicated that the different methods of measuring internal and surface checking were effectively the same at the genetic level. However, the fact that correlations between surface- and internal checking traits were only moderate and significantly different from +1 suggests that these traits were under the control of somewhat different suites of genes. The concentration of internal checks within growth rings (Fig. 4.1) indicated that internal checking was principally driven by variation in collapse between latewood and earlywood but surface checking may have been driven by other factors unlikely to substantially affect internal checking, such as shrinkage anisotropy (Svensson and Martensson, 1999). The significant and positive genetic correlation between wedge basic density and board surface check length was further evidence that surface checking in this study was driven by factors other than collapse, given evidence from previous studies of a strongly negative genetic

correlation between basic density and collapse (Hamilton et al., 2009b, Kube, 2005). Future studies should aim to clarify the strength and direction of these correlations and to identify more effective non-destructive means of predicting checking in standing trees.

Checking in sawn boards is expensive to assess directly, as board genetic identity must be tracked through processing and drying. However, this study has shown that genetic variation in internal checking can be assessed by air-drying a wedge taken from a disk cut from a log prior to processing. It may be possible to assess internal checking from small wood blocks taken from standing trees, although the samples would need to be of sufficient size to generate the stresses that cause checking to develop during drying (Fig. 4.1). Although estimates of shrinkage and collapse can be obtained from 12 mm diameter increment cores (Hamilton and Potts, 2008), these cores are probably not of sufficient size to reliably evaluate internal checking.

Inter-trait genetic correlations between core shrinkage traits (refer to Hamilton et al. 2009b for details) and the four checking traits assessed in this study were generally positive and moderate to strong but not significantly different from zero. For example, genetic correlations between core shrinkage plus collapse and sawn-board checking traits were all >0.63 but only that with wedge internal checking score was significantly different from zero ($P < 0.01$). However, these estimates were based on only 29 common families for which both core shrinkage and checking data were collected. A study including a greater number of common families is required for the precise estimation of genetic correlations between non-destructively assessed core shrinkage traits and commercially-important checking traits.

Due to mortality during stand development and the requirement to select logs of suitable size and straightness for sawing, the genetic parameters presented in this study are for a subset of both the planted, and surviving (to age 14 years) *E. nitens* base population. Most studies of the genetics of wood properties are similarly based on a selected subset of the population,

as trees need to be of a suitable size for assessment, whether it be for coring (Stackpole et al., 2010) or solid-wood processing (Hamilton et al., 2009a). Within the upper and lower log diameter restrictions of the processing system, we selected a set of trees with a frequency distribution similar to that of the entire population at age 14 years. In addition, log straightness was a mandatory requirement for the sawmill, so only trees meeting the straightness criterion of no more than $1/5$ small-end diameter displacement over the log length were processed. Growth (average $\hat{h}_{op}^2 = 0.26$) and stem form (average $\hat{h}_{op}^2 = 0.28$) have low to moderate narrow-sense heritabilities in *E. nitens*, and growth and at least wood density appear to be negatively genetically correlated (Hamilton and Potts, 2008). The possibility that we have underestimated the levels of additive genetic variation in wood property traits and the strength of additive genetic correlations between traits cannot be dismissed. However, the similarity of our estimate of the coefficient of additive genetic variation in basic density (5%) to that of the average of previous estimates from earlier age sampling for pulpwood regimes (4.5%) (Hamilton and Potts, 2008, Hamilton et al., 2009b), suggests that any bias is likely to be relatively small.

4.4 Conclusion

This study showed that there is a genetic basis to variation in both stiffness and checking in *E. nitens*, indicating that the quality of structural- and appearance-grade timber could be improved with selective breeding. The genetic correlation between standing-tree AWV and static MOE in boards was very strong, indicating that standing-tree AWV could be adopted as an indirect but effective and non-destructive selection tool for improving wood stiffness. An equivalent non-destructive assessment methodology for checking traits was not identified. However, a destructive methodology involving sampling-disk wedges does appear promising for assessment of board checking. Internal checking was genetically positively correlated between boards and the wedge assessments. In addition, there was a

significant positive genetic correlation between basic density and surface check length. However, this correlation is adverse as high density is favoured in both pulpwood and solid-wood production systems, and further investigation into the drivers of this relationship, its repeatability across environments and its relative economic impact is required.

5.0 CHAPTER 5. GENETIC VARIATION IN TRAITS AFFECTING SAWN TIMBER RECOVERY IN PLANTATION GROWN *EUCALYPTUS NITENS*

5.1 Introduction

In Australia, supplies of sawlogs from native eucalypt forests are declining, and the prospective role of eucalypt plantations for sawlog supply has received much attention. While most eucalypt plantations are grown for pulp-wood production, there is an increasing world-wide estate of eucalypt plantations grown for solid-wood products, including structural timber for construction, and appearance-grade products such as profile mouldings, flooring, furniture and wall-panelling (Donnelly et al., 2003). Small diameter sawlogs from unthinned and unpruned plantations are generally not suitable for the production of appearance-grade sawn timber because of defects due to knots, low green-board recoveries, poor durability and drying defects (Nolan et al., 2005). However, such logs can be processed for structural timber, finger-jointed products, knotty appearance products, or veneered for plywood laminates and reconstituted solid-wood products such as laminated-veneer-lumber.

The past two decades have seen rapid growth of the Australian eucalypt hardwood plantation estate, which in 2010 approached one million hectares (Bureau of Rural Sciences, 2010). The Australian plantation estate of *Eucalyptus nitens* is approximately 200,000 ha, over 70% of which is located in Tasmania (Parsons et al., 2006). The species is favored where low temperatures (Tibbits and Hodge, 2003), or *Mycosphaerella* leaf disease (Mohammed et al., 2003) restrict the growth or survival of *E. globulus*. Twenty-five thousand hectares of Tasmanian *E. nitens* plantations are now being grown under sawlog silvicultural regimes and additional areas of sawlog plantations are under development by other companies.

Research has recently been undertaken on wood processing requirements and technologies for sawn wood production from plantation eucalypts (Washusen et al., 2009). One option to enhance economic performance is to improve tree, log and wood characteristics (traits) through breeding. Log diameter determines whether a log can be processed for solid timber or is sent for alternative types of processing. This segregates the logs from a plantation into different production systems with dissimilar cost and revenue structures. Diameter also has a major bearing on the selection of sawing strategy and influences the proportions of back-sawn, quarter-sawn and mixed-sawn boards extracted from each log (Washusen and Innes, 2007). In turn, the sawn-board type influences board characteristics such as drying defects and shrinkage, and hence board value. Increasing log diameter will generally result in a higher volume recovery of high-value select and standard grades as a proportion of log volume (Washusen and Innes, 2007).

Stem straightness influences the length of acceptably straight sawlog that can be obtained, and in turn the volume of green-boards (i.e. sawn timber prior to drying) recovered from the tree. There is typically a maximum permissible log sweep (deviation of the stem's longitudinal axis from a straight line), which largely depends on the sawing system employed to process the logs. Excessive sweep results in logs being processed for alternative products such as pulp. It is difficult, time-consuming and therefore expensive to directly measure the straightness of standing tree stems, making it unfeasible to physically measure stem straightness of all the trees in a large research trial or plantation. Therefore visual assessment methods ranking trees into stem straightness categories have been widely adopted for evaluation of stands prior to harvesting and for stem assessment in tree breeding trials (Macdonald et al., 2009).

Stem taper is the rate of decrease in stem diameter per unit length of stem. Taper may vary along the stem depending on tree, stand, site characteristics and silvicultural history (Larson, 1963). For a given stem diameter at breast height, increasing log taper will reduce the recovery of green sawn boards.

Plantation-grown eucalypts are known to exhibit high levels of longitudinal growth stresses in the peripheral layers of the stem (Yang et al., 2001, McKenzie et al., 2003b), the release of these growth stresses during tree felling and crosscutting of logs can lead to a high incidence and severity of log end-splitting (McKenzie et al., 2003b, Valencia et al., 2010). Valencia et al. (2010) demonstrated that log end-splitting was a significant predictor of green-board end-splitting in *E. nitens*, which affects overall total green-board volume recovery. In sawing small diameter plantation eucalypts, multi-saw single-pass linear sawing systems with chippers that first remove the outer peripheral wood, have the advantage over single-saw systems by symmetrically releasing growth stresses during processing. This can reduce losses due to board deflection (e.g. bow and spring) and end-splitting and therefore improve green sawn-board recoveries (Washusen et al., 2009, Blakemore et al., 2010, Washusen and Innes, 2007).

A breeding objective is a combination of biological traits that tree growers and/or timber processors wish to genetically improve for a particular end product (Borralho et al., 1993, Greaves et al., 1997b). While there has been extensive research on breeding *E. nitens* for the pulp and paper industry (Greaves et al., 1997b, Borralho et al., 1993), breeding objectives for solid-wood products and the associated potential for genetic improvement are less clear, particularly in the face of changing processing technologies and products (Raymond, 2002, Kube et al., 2001a). Determining which traits should be included in breeding objectives for solid-wood products is the subject of on-going research. Sawlog volume production will clearly affect the profitability of sawmilling enterprises and will be included in a solid-wood breeding objective. Traits linked to green-board recovery and value, such as wood strength, dimensional stability and appearance characteristics such as checking (Blackburn et al., 2010, Hamilton and Potts, 2008) will also be relevant. While relatively unimportant for pulpwood (Borralho et al., 1993, Greaves et al., 1997b), tree architecture traits such as stem straightness,

stem taper, frequency of forking and branch characteristics can also affect green-board recovery and value.

In tree improvement programs, breeders rarely wait until harvest-age before selecting the most favourable genotypes for further breeding or deployment. A set of selection criteria is used (e.g. core wood basic density, tree diameter at breast height and stem straightness score), which are easily and cost effectively measured at a young age (Ponzoni and Newman, 1989, Hamilton et al., 2010). Ideally these criteria are strongly genetically correlated with the harvest-age objective traits and therefore provide the tree breeder with information about traits in the breeding objective. To achieve gains in objective traits requires both the selection criteria and objective traits to be under genetic control (Falconer and Mackay, 1996) and correlated with each other. Breeding for two or more traits simultaneously means tree breeders must gauge the strength, stability and direction (+/-) of the genetic correlations between selection criteria and all chosen objective traits (White et al., 2007).

The aim of this study was to estimate heritabilities and determine the strength of genetic correlations among selection-age growth criteria and harvest-age objective traits that impact upon wood volume and green-board volume recovered at processing of *E. nitens*. The commercial production system under study involved the sawing of logs from unpruned, unthinned *E. nitens* plantations into sawn boards for structural applications, using a HewSawTM R200 linear sawmill (Cannon and Innes, 2007). We studied a fourteen-year-old *E. nitens* progeny trial established in 1993 to determine whether traits affecting green-board volume recovery are under genetic control at the race and within-race (additive) level, and the extent to which early-age DBH is correlated with green-board volume, harvest-age stem straightness, log acceptability for sawing and log end-splitting.

5.2 Materials and methods

5.2.1 Progeny trial

This study was undertaken on an *E. nitens* base-population progeny trial established near Tarraleah (latitude 42°18' S, longitude 146°27' E) in central Tasmania. The trial was established on a site 600 m above sea level with a mean annual rainfall of approximately 1 200 mm. The trial comprised families derived from open-pollinated seed from 420 native-forest parent trees sampled from twenty-eight localities. Sampled localities extended over most of the natural range of *E. nitens* in the central highlands region of Victoria and encompassed three geographically and genetically distinct races: Southern, Northern and Connor's Plain (Hamilton et al., 2008). The trial was established as a randomised incomplete block design comprising six replicates, each of twenty-one incomplete blocks, containing twenty families represented by a five-tree row-plot. Initial spacing was 4 m between rows and 2 m between trees within rows. Fertiliser (100 g of superphosphate and 125 g of 20:10:0 N:P:K) was applied to each tree three months after planting. No thinning or pruning was undertaken in the trial.

5.2.2 Tree assessment and selection

At age fourteen years all surviving tree stems in the trial replicates 1-3 which were scheduled for harvesting, were measured for diameter at breast height (DBH₁₄) using a diameter tape and the survival of each tree was recorded as 1-alive and 0-dead. Diameter at breast height had previously been assessed on all surviving trees in replicates 1-5 at ages four (DBH₄) and nine (DBH₉) years. Replicate 6 was not assessed at ages four and nine. Trees selected for the processing study had to meet a supply contract log size criteria of 15 cm minimum small-end and 28 cm maximum large-end diameter under bark. Small-end diameter was estimated at a butt-log length of 5.6 m using a log taper value derived from data supplied by Forest Enterprises Australia Ltd. The logs also had to have acceptable straightness, with log sweep less than 20% of small-end diameter.

The straightness score categories used in these trials were: 6 (no stem deviation visually apparent), 5 (deviation 1–25 % of small-end diameter), 4 (deviation 26-50 % of small-end diameter), 3 (deviation 51-75 % of small-end diameter), 2 (deviation 76-100% of small-end diameter) and 1 (deviation >100 % of small-end diameter). These deviations were estimated visually to approximately 8 m height of stem. The method allowed the identification of stems that satisfied contractual log supply sweep requirements, enabled a ranking of phenotypes present at this site and allowed the estimation of the coefficient of additive variation for this trait. This method was recently developed by Forestry Tasmania. Prior to full trial assessment, to establish consistency between assessors and confirm correct estimates would be made, a random sample of twenty visually independently assessed scores were compared. It was determined that visual stem straightness scores of 5 and 6 would meet the log-sweep requirement over the first six meters of stem height.

As far as possible, selected trees from each family were chosen such that all three harvested replicates were represented and families had a minimum of four trees sawn. A total of 560 trees from 129 families were selected for sawing.

Selected trees were harvested, with an average stump height of 0.25 m and the butt-log was cut from each felled tree and de-barked. To reduce the incidence of log end-spitting, log ends were reinforced with MiTek GS-16-gauge gang-nail plates and coated with Dussek-Campbell log-grease. Identities of the selected trees were maintained during harvesting and transport using a wooden identity plug glued into a hole drilled in the standing tree just above the bottom end of the log, as described by Blackburn et al. (2010).

5.2.3 Assessment of log-end splitting and log taper

At the sawmill, 50 mm disks with the gang nails attached were removed from both ends of each log. The following day, log lengths and the largest and

smallest diameters at each end were measured, and end-splitting was assessed within an eight hour period, using the Log Split Index Method 2 (Yang, 2005). This method was chosen as it includes measurement of splits which extend to the log periphery and along its longitudinal surface. The method sums the estimated area of the log-end split plane and divides the sum by the square of the log-end radius, thus adjusting for log-end diameter in the index value. Log-taper was calculated as the difference between the small- and large-end log-end radii divided by the log length, expressed as cm m^{-1} of log length.

5.2.4 Log processing and assessment of log and green board volume

The harvested logs were processed by normal sawmill operations into structural timber for building and construction (Cannon and Innes, 2007). At the sawmill log intake, optical scanning indicated that sixty-four logs exhibited excessive sweep, and these logs were rejected. Subsequent assessment of these logs showed that the log-scanner was out of calibration and only 13 should have been rejected. The accepted logs were sawn with a R200 HewSawTM. This mill chips and saws small-diameter logs in a single pass, so peripheral growth stresses on opposite sides of the stem are released simultaneously, minimising deflection of green boards off the saw (Washusen and Innes, 2007). Logs were batched into five size classes based on their small end diameter, and for each diameter class one cutting pattern was used to produce two, three, four, or six boards per log (Fig. 5.1, Table 5.1). Visual grading of the boards (Standards Australia, 2000) into 'reject' or 'acceptable' classes was undertaken at mill operating speed within the confines of a restricted workspace, therefore it was not possible to retain rejected boards for further assessment. For this reason 100% green-board recovery was assumed from the cutting pattern assigned to each log. The 'Frustum of a Cone' equation (Eshbach, 1975) was used to calculate log volume. Board cutting pattern dimensions (Table 5.1) and individual log lengths were used to determine green-board volumes per log.

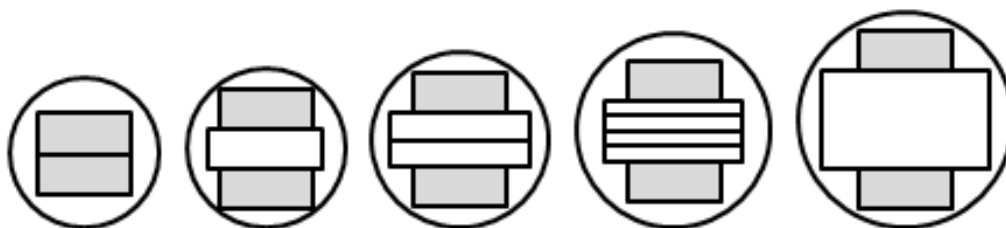


Figure 5.1 Log cutting patterns (A-E).

Cutting pattern board dimensions shown in Table 5.1

Table 5.1 Log dimensions, number of logs processed, rankings of mean stem straightness, number of green boards extracted and their dimensions for each cutting pattern.

Cutting profile	Number of logs processed	Log small-end diameter range cm	Mean small end diameter cm	Mean stem-straightness rank	Green boards recovered and dimensions mm
A	17	15.0 - 16.9	15.9	5.1	2 off, 106 x 45
B	31	17.0 - 17.9	17.5	5.4	2 off, 106 x 45 1 off, 130 x 45
C	106	18.0 - 19.9	18.9	5.6	2 off, 106 x 45 2 off, 160 x 30
D	165	20.0 - 21.9	20.9	5.5	2 off, 106 x 45 4 off, 155 x 17
E	159	22.0 - 27.0	24.9	5.7	2 off, 106 x 45 1 off, 190 x 110

5.2.5 Statistical analyses

For traits assessed on all trees within replicates (i.e. DBH₄, DBH₉, DBH₁₄, stem straightness and survival), the following linear mixed model was fitted in ASReml 2.0 (Gilmour et al., 2006) to perform univariate restricted maximum likelihood analyses:

$$Y = \text{MEAN} + \text{REP} + \text{RACE} + \text{IBLOCK}(\text{REP}) + \text{PLOT}(\text{IBLOCK}) + \text{FAMILY}(\text{RACE}) + \text{RESIDUAL} \quad (5.1)$$

where; Y is the observation, MEAN is the mean, REP is the fixed replicate effect, RACE is the fixed race effect, *IBLOCK*(REP) is the random incomplete

block within replicate effect, *PLOT(IBLOCK)* is the random plot within incomplete block effect, *FAMILY(RACE)* is the random family within race effect and *RESIDUAL* is the residual. As trees selected for the sawn-board processing trial represented a small sub-set of the entire progeny trial, terms for *IBLOCK(Rep)* and *PLOT(IBLOCK)* were omitted from the analysis of log and green-board traits. For all traits under test the residuals were observed to be approximately normally distributed.

To estimate genetic parameters for traits measured on selected trees only (i.e. DBH₁₄ selected trees, log volume and log-end split indices) a series of trivariate analyses were undertaken including DBH₁₄, stem straightness and the trait for which parameters were being estimated. Trivariate analyses were undertaken instead of univariate analyses in an effort to account for possible bias introduced through the selection of stems suitable for sawmilling. It was not possible to fit multivariate models including more than three traits due to convergence difficulties. The trivariate model included the same explanatory factors as the univariate model and allowed for covariation between random effects. However, plot and incomplete block terms were fitted for DBH₁₄ and stem straightness only.

The additive variance (σ_{add}^2), phenotypic variance (σ_{pheno}^2), open-pollinated narrow-sense heritability (h_{op}^2) and percentage coefficient of additive variation ($\text{CV}_{\text{add}}\%$) were estimated for each trait as follows:

$$\sigma_{\text{add}}^2 = \frac{\sigma_{\text{fam}}^2}{r} \quad (5.2)$$

$$\sigma_{\text{pheno}}^2 = \sigma_{\text{fam}}^2 + \sigma_{\text{plot}}^2 + \sigma_{\text{residual}}^2 \quad (5.3)$$

$$h_{\text{op}}^2 = \frac{\sigma_{\text{add}}^2}{\sigma_{\text{pheno}}^2} \quad (5.4)$$

$$CV_{add \%} = 100 \times \frac{\sqrt{\sigma_{add}^2}}{\bar{x}} \quad (5.5)$$

where σ_{fam}^2 , σ_{plot}^2 and $\sigma_{residual}^2$ are the variance components for *FAMILY(RACE)*, *PLOT(IBLOCK)* and *RESIDUAL* respectively, r is the coefficient of relationship among individuals within open-pollinated families, set at 0.4 to account for an assumed selfing rate in open-pollinated families of 30% (Griffin and Cotterill, 1988) and \bar{x} is the mean. For traits assessed on the selected population the plot term was not included in the mixed model and thus their σ_{pheno}^2 did not include σ_{plot}^2 . The significance of the σ_{fam}^2 was tested using a ‘one-tailed’ likelihood ratio test (Self and Liang, 1987). The variance components for survival were estimated using a binomial model with a probit link function (Gilmour et al., 2006), and the significance of σ_{fam}^2 was assessed using a Z test. The significance of the fixed RACE term for each trait was gauged with a Wald F-test, where *FAMILY(RACE)* was the error term and the approximate denominator degrees of freedom were computed using the numerical derivatives method (Gilmour et al., 2006).

Bivariate analyses were undertaken to estimate pair-wise covariances among random terms. Additive genetic correlations (r_a) were estimated according to the following function:

$$r_{a_{12}} = r_{fam_{12}} = \frac{\sigma_{fam_{12}}}{\sqrt{\sigma_{fam_1}^2 \sigma_{fam_2}^2}} \quad (5.6)$$

where $r_{fam_{12}}$ is the *FAMILY(RACE)* correlation between traits 1 and 2, $\sigma_{fam_{12}}$ is the *FAMILY(RACE)* covariance component between traits 1 and 2 and $\sigma_{fam_1}^2$ and $\sigma_{fam_2}^2$ are the *FAMILY(RACE)* variances for traits 1 and 2 respectively.

Significance tests of inter-trait genetic correlations against zero were conducted using a ‘two-tailed’ likelihood ratio test and against one or minus one, as appropriate, using a ‘one-tailed’ likelihood ratio test (Gilmour et al.,

2006). Inter-trait Pearson's correlation among phenotypic observations were estimated and two tailed t-tests were used to test if phenotypic correlations were significantly different from zero.

The significance of differences among the trait means for the five different cutting patterns was tested using a single factor fixed effect model fitted with the Proc Mixed procedure of SASTM (version 9.1) and a Tukey-Kramer adjustment used for assessing the significance of pairwise comparisons.

5.3 Results

At the pre-harvest progeny trial assessment, approximately 86% of planted trees were surviving. Survival at earlier ages was not determined due to incomplete assessment of the trial. At age fourteen there was no significant race difference in survival, but highly significant ($P < 0.001$) differences among races in DBH and stem straightness were evident (Table 5.2). There was no significant difference in DBH between races in the subset of 560 trees selected for sawing, however there were significant differences in log-taper ($P < 0.001$), log volume ($P < 0.05$) and green-board recovery ($P < 0.01$). No significant differences between races were detected in the end-split index on the lower and upper logs. The Southern race clearly had the most favourable trait values for sawing. It had the greatest growth, greatest volume, least taper and straightest logs when compared to mean values for the Northern and Connor's Plain races (Table 5.2).

In addition to race differences, all traits except log taper and green-board recovery showed significant ($P < 0.05$) family and thus additive genetic variation within races (Table 5.2). While survival differences were not evident between races, within races the heritability at age fourteen was 0.25 and highly significant. The h_{op}^2 for DBH at different ages ranged from 0.17 to 0.20 and for tree stem straightness at age fourteen years was 0.17. For the subset

of trees selected for sawing, the h_{op}^2 for DBH was 0.33, higher than that in the total trial population at the same age and h_{op}^2 of log volume was 0.20.

Heritability ($h_{op}^2 = 0.46$) for upper end-splitting was the highest of all traits, and much greater than the corresponding value for lower-end splitting ($h_{op}^2 = 0.28$). The coefficient of additive genetic variation for DBH of the selected trees (5%) was approximately half that of the total population (Table 5.2).

Additive genetic correlations (r_a) among DBH at all ages assessed in the full progeny trial, as well as between all DBH measures and log volume were strongly positive ($r_a = 0.87$ to 0.99), highly significant ($P < 0.001$) and increased with age (Table 5.3). Genetic correlations between DBH and stem straightness were highly significant, positive and relatively stable for the three DBH ages ($r_a = 0.67$ to 0.78). End-splitting of the upper log was significantly, moderately and positively correlated with DBH_{14} at the genetic and phenotypic level and with DBH_9 at the genetic level (Table 5.3). The genetic and phenotypic correlations between upper and lower log end-splitting were significant and positive ($r_a = 0.55$ and $r = 0.26$ respectively).

Table 5.2 Race means, P-values (to test the significance of race differences), overall trial mean, additive variance, narrow-sense heritability (h_{op}^2) and coefficient of additive variation ($CV_{add}\%$) for studied traits, with standard errors in parenthesis.

Trait	Southern	Race mean Northern	Connor's Plain	Race P-value	Overall trial mean	Additive variance	h_{op}^2 (SE)	CV_{add} %
DBH ₄ cm	11.5 (0.09)	11.5 (0.10)	11.5 (0.18)	ns	11.5 (0.09)	0.62 (0.08) ***	0.17 (0.02)	7
DBH ₉ cm	17.2 (0.12)	16.7 (0.14)	16.5 (0.36)	**	17.2 (0.14)	2.92 (0.48) ***	0.20 (0.02)	10
DBH ₁₄ cm	21.5 (0.18)	20.3 (0.16)	19.6 (0.31)	***	21.5 (0.10)	3.30 (0.35) ***	0.19 (0.03)	9
Survival binary 1-alive 0-dead	0.86 (0.01)	0.87 (0.01)	0.86 (0.02)	ns	0.86 (0.01)	0.12 (0.01) ***	0.25 (0.03)	N/A
Stem straightness	4.3 (0.05)	4.0 (0.05)	3.7 (0.08)	***	4.3 (0.04)	0.1 (0.01) ***	0.17 (0.02)	8
DBH ₁₄ cm selected trees	26.9 (0.14)	26.91 (0.32)	26.4 (0.63)	ns	26.9 (0.24)	2.03 (0.67) ***	0.33 (0.10)	5
Log taper cm m ⁻¹	0.40 (0.01)	0.47 (0.02)	0.49 (0.03)	***	0.40 (0.01)	0.003 (0.00) ns	0.14 (0.09)	12
Log volume m ³	0.250 (0.00)	0.232 (0.00)	0.223 (0.01)	*	0.250 (0.00)	0.003 (0.00) ***	0.20 (0.11)	23
Green board volume m ³	0.122 (0.00)	0.113 (0.00)	0.099 (0.01)	***	0.122 (0.00)	0.001 (0.00) ns	0.17 (0.027)	25
Lower log endsplit index	0.72 (0.04)	0.70 (0.09)	0.58 (0.17)	ns	0.72 (0.04)	0.009 (0.00) **	0.28 (0.09)	14
Upper log endsplit index	0.80 (0.04)	0.80 (0.08)	0.80 (0.15)	ns	0.80 (0.04)	0.013 (0.00) ***	0.46 (0.11)	14
* P<0.05, ** P<0.01, *** P<0.001								
N/A Not Applicable								

Table 5.3. Inter-trait genetic (below diagonal) and phenotypic (above diagonal) correlations with standard errors in parenthesis. Additive genetic correlations involving stem taper and green-board volume were not calculated as no significant additive genetic variation was detected for these traits.

Trait	DBH ₄ cm	DBH ₉ cm	DBH ₁₄ cm	survival binary 1-alive 0-dead	stem straightness	DBH ₁₄ cm selected trees	Log taper cm m ⁻¹	Log volume m ³	Green board volume m ³	Lower log-end split index	Upper log-end split index
DBH ₄ cm		0.91 (0.01) ***	0.82 (0.01) ***	0.36 (0.01) ***	0.47 (0.01) ***	0.36 (0.05) ***	0.49 (0.05) ns	0.27 (0.06) ***	0.26 (0.05) ***	-0.003 (0.05) ns	0.03 (0.05) ns
DBH ₉ cm	0.92 (0.01) ***		0.96 (0.01) ***	0.36 (0.01) ***	0.58 (0.01) ***	0.79 (0.04) ***	0.13 (0.05) *	0.51 (0.05) ***	0.57 (0.05) ***	0.11 (0.05) *	0.06 (0.05) ns
DBH ₁₄ cm	0.88 (0.02) ***	0.99 (0.01) ***		0.47 (0.01) ***	0.61 (0.01) ***	1.01 (0.01) ***	0.14 (0.04) **	0.67 (0.04) ***	0.75 (0.04) ***	0.20 (0.04) ***	0.12 (0.04) **
Survival binary 1-alive 0-dead	0.80 (0.04) ***	0.75 (0.04) ***	0.65 (0.04) ***		0.01 (0.01) ns	N/A	-0.05 (0.04) ns	0.01 (0.05) ns	0.02 (0.05) ns	0.03 (0.04) ns	0.08 (0.04) ns
Stem straightness	0.67 (0.05) ***	0.78 (0.04) ***	0.78 (0.04) ***	0.57 (0.05) ***		0.39 (0.19) ns *** (1)	-0.10 (0.04) *	0.16 (0.05) ***	0.22 (0.05) ***	0.02 (0.04) ns	-0.04 (0.04) ns
DBH ₁₄ cm selected trees	0.56 (0.15) **	0.96 (0.03) ***	1.01 (0.01) ***	N/A	0.18 (0.04) ***		0.14 (0.04) **	0.67 (0.04) ***	0.75 (0.04) ***	0.20 (0.04) ***	0.12 (0.04) **
Log taper cm m ⁻¹	N/A	N/A	N/A	N/A	N/A	N/A		0.04 (0.05) ns	-0.19 (0.05) ns	0.05 (0.04) ns	0.05 (0.04) ns
Log volume m ³	0.87 (0.04) ***	0.98 (0.02) ***	0.99 (0.01) ***	N/A	0.32 (0.13) ns	0.96 (0.03) ***	N/A		0.59 (0.05) ***	0.04 (0.05) ns	0.02 (0.05) ns
Green board vol m ³	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A		0.15 (0.05) ***	0.10 (0.05) *
Lower log-end split index	0.06 (0.26) ns	0.39 (0.19) ns	0.32 (0.18) ns	N/A	-0.35 (0.29) ns	-0.13 (0.26) ns	N/A	0.07 (0.26) ns	N/A		0.26 (0.04) ***
Upper log-end split index	0.29 (0.19) ns	0.44 (0.16) *	0.44 (0.15) *	N/A	-0.22 (0.23) ns	0.17 (0.19) ns	N/A	0.31 (0.19) ns	N/A	0.55 (0.23) *	
ns Not significantly different from zero, * P<0.05, ** P<0.01, *** P<0.001				N/A Not Applicable							

As diameter increased, and applied cutting patterns changed from A to E (Fig. 5.1, Table 5.1), the percentage of green-sawn-board volume recovered from the log generally increased as expected (Table 5.4). There was an approximately two-fold increase in green-board volume recovered between the smallest diameter range cutting pattern (A) and the patterns for the larger diameters (B-E). Pairwise comparison of log cutting pattern treatments showed that significant differences existed among levels of green-board volume recovered in different diameter classes (Table 5.4), which demonstrated the important influence of log diameter on product recovery and hence on the economics of processing *E. nitens* plantation sawlogs. For the upper and lower log-end split index, the larger cutting pattern classes generally differed significantly from one another, with more splitting occurring in logs cut with the E pattern.

Table 5.4. Means of recovery traits for different log cutting patterns with standard errors in parenthesis. Common letters indicate treatments that are not significantly different ($P < 0.05$), following a Tukey-Kramer adjustment for pairwise comparisons.

Cutting profile treatment	Mean DBH (SE) (cm)	Mean log taper (SE) (cm m ⁻¹)	Mean split index (SE) Lower log-end	Mean split index (SE) Upper log-end	Mean log volume (m ³) (SE)	Greenboard volume (m ³) (SE)	Greenboard recovery (%)
A	23.6 (0.32) a	0.54 (0.064) c	0.506 (0.16) ab	0.776 (0.16) ab	0.164 (0.005) a	0.042 (0.0002) a	26.0
B	24.0 (0.24) a	0.46 (0.021) b	0.750 (0.12) ab	0.688 (0.19) ab	0.181 (0.003) b	0.085 (0.0002) b	46.7
C	25.0 (0.14) b	0.37 (0.010) ab	0.558 (0.06) a	0.590 (0.07) a	0.202 (0.002) c	0.103 (0.0001) c	50.9
D	26.7 (0.11) c	0.42 (0.008) ab	0.689 (0.05) ab	0.870 (0.06) b	0.242 (0.002) d	0.107 (0.0001) d	44.4
E	29.4 (0.11) d	0.41 (0.015) a	0.854 (0.05) b	0.888 (0.06) b	0.301 (0.002) e	0.159 (0.0001) e	52.8

5.4 Discussion

In this study DBH heritability was relatively stable between early (four years) and later ages (nine and fourteen years) and additive genetic correlation estimates amongst all ages of DBH and between survival at age 14 years, and early-age DBH were strongly positive and highly significant. This high correlation indicates that early-age DBH could be used to select for improved later-age survival and could also be an effective selection criterion for breeding to improve harvest-age DBH and the volume of timber recovered per hectare. The estimates of narrow-sense heritabilities for DBH at all ages, survival and inter-age genetic correlations for DBH were similar to other published estimates for open-pollinated progeny trials of *E. nitens* (Hamilton and Potts, 2008). These estimates were also comparable to those reported for the related temperate species *E. globulus*. For example, Stackpole et al. (2010) found similar positive genetic correlations between DBH and survival at age 16 years, while Chambers et al. (1996) also observed positive correlations between early age DBH and survival in *E. globulus*.

Low heritability and coefficient of additive genetic variance for stem straightness indicated it would be difficult to make rapid gains if selecting for this trait within races, although significant between race variation was observed and the more favourable mean value of the Southern race could be exploited. Our estimates of these genetic parameters were within the range of those previously reported for stem straightness in *E. nitens* (Hamilton and Potts, 2008), similar to studies in other eucalypt species (Arnold et al., 2004), but heritability was lower than that recently reported for *E. globulus* grown in Western Australia (Callister et al., 2011).

In this study the relatively stable, strongly positive and highly significant additive genetic correlations between DBH at all ages and stem straightness, indicated that early-age DBH could be used as a surrogate selection criterion to improve stem straightness in tree breeding programs. It is possible that

this strong correlation between stem straightness and DBH may, in part, have been an artefact of scoring stem straightness as a proportion of stem diameter. However, when individual phenotypic stem straightness scores were adjusted for tree diameter (based on simple linear regression parameter estimates derived from a model that fitted stem straightness as the response variable and DBH as the explanatory variable), strongly positive additive genetic correlations were still evident. This was indicative of a strong correlation between DBH and actual deviations from straightness. These findings support those of Hamilton and Potts (2008) review of *E. nitens* genetic parameters, which also reported favourable average genetic correlations between DBH and stem straightness and the study by Callister et al. (2011) in *E. globulus*.

For all three races the incidence of log end-splitting was higher at the small end than the large end. This longitudinal trend has been previously observed in processing performance studies (Valencia et al., 2010, Washusen et al., 2009). Moderate heritabilities of both upper and lower log end-splitting and a low to moderate coefficient of additive genetic variation indicates that these traits could be improved through breeding. The potential to reduce end-splitting through breeding has also been demonstrated in *E. grandis* by Telles dos Santos et al. (2004) who found moderate to high levels of heritability ($h^2 = 0.31$) for log end-splitting index. Inter-trait genetic correlations between upper log end-splitting and all other traits assessed in the current study indicate that an unfavourable genetic relationship exists between diameter and log end-splitting in *E. nitens*.

Log and board end-splitting are difficult to predict in *E. nitens*, as levels of peripheral growth stress, which is associated with splitting, are not closely correlated with any single growth parameter, but are influenced by a combination of factors that influence the tree at different ages and tree heights, depending on stand age and stocking (Biechele and Nutto, 2008). In twenty-two year old *E. nitens* trees, harvested from an un-pedigreed plantation thinning trial in Tasmania, end-splitting was phenotypically

positively correlated with DBH (Valencia et al., 2010) and this was also seen in this study. An earlier study in *E. nitens* showed log end-splitting to be correlated to the percentage of heartwood, but not with log diameter (Purnell, 1988). However, in the present study, although heartwood was not assessed, the correlation with DBH was low (≤ 0.2) and there were only minor differences, albeit significant ones, in mean end-split scores across the five cutting patterns, for both the lower and upper ends of the log (Table 5.4). Furthermore, because the trail processing was under normal sawmill operations the relationship between the Log End-Split-Index-2 and the volume loss to board end-splits could not be determined. A significant relationship has been demonstrated between this log split index and the volume of board lost to end docking in both *E. globulus* (Yang and Pongracic, 2004) and *E. nitens* (Valencia et al., 2010). A positive genetic correlation between tree diameter and log end splitting index suggests that volume gains from breeding, could be countered to some extent by subsequent volume losses through board splitting. This was demonstrated in a Tasmanian *E. nitens* sawn-board study, where end-docking of boards to remove end-splitting was shown to produce a significant loss in merchantable green-board volume, ranging from a 4.2 – 9.5 percent loss in volume for quarter-sawn and back-sawn boards respectively (Washusen et al., 2007).

5.5 Conclusion

This study showed significant race and within-race genetic differences exist in, harvest-age stem diameter and straightness as well as log volume in *E. nitens*, indicating these traits are amendable to genetic improvement. Log taper and green-board volume were shown to have significant genetic differences at the race level. Strongly positive genetic correlations among DBH at different ages and survival, and between DBH at year four and log volume, demonstrated that early-age DBH would be an effective selection criterion for breeding to improve harvest-age DBH and log and green-board volume recovery. However, significant adverse genetic correlations were observed between log end splitting and DBH at ages 9 and 14 years,

indicating that selection for greater DBH may increase log-end splitting. Favourable genetic correlations between DBH at all ages and stem straightness indicated that early-age DBH may potentially be used as a cost-effective surrogate selection trait to improve tree stem straightness in *E. nitens* breeding programs.

6.0 CHAPTER 6. GENETIC CORRELATIONS BETWEEN PULPWOOD AND WOOD STIFFNESS TRAITS APPEAR FAVOURABLE IN *EUCALYPTUS NITENS*

6.1 Introduction

There is increased pressure for timber processors to now provide quality forest products from plantation sawlogs. However, compared to sawlogs from native forests, logs from rapidly grown plantations do not have the higher quality wood properties required for higher value architectural and structural solid sawn timber products. The forest products industry has responded by using adhesives to bond wood fibres, veneers or saw-timber together to manufacture high-performance engineered wood products such as medium density fibreboard, plywood, laminated veneer lumber and glulam beams (EWPAA, 2008). For a given timber resource, plywood engineered wood products have a greater strength than sawn timber of the same dimensions and may be used over a wider range of applications (EWPAA, 2008). Plywood engineered wood products are manufactured with specific veneer arrangements (based on grain orientation and veneer sheet strength and appearance characteristics) to provide optimal performance in their intended application. The wood properties of the tree have a major bearing on the final quality and strength of peeled veneer and in turn the performance of the final engineered product.

Australia's National Forest Policy Statement of 1992 provided the basis for development of the Regional Forest Agreements and in 1997, the Plantations for Australia 2020 Vision was launched to enhance regional wealth and international competitiveness in Australia's plantation resources. The 2020 Vision aimed to treble the area of commercial tree crops by 2020 and the plantation estate has subsequently expanded, driven by 'Managed Investment Schemes' with favourable tax incentives to attract investors (IFA, 2010). Until recently softwood (coniferous) log supplies have met most of the raw resource demand for plywood products in Australia, but these changes in

government policy resulted in increased investment in eucalypt plantations, with the total area now approaching one million hectares (Bureau of Rural Sciences, 2010). The Australian plantation estate of *Eucalyptus nitens* is approximately 200 000 ha of which Tasmania has approximately two-thirds (Bureau of Rural Sciences, 2007). *Eucalyptus nitens* is planted where the more widely favoured *E. globulus* cannot be grown because of low temperatures or susceptibility to disease. Over 80% of *E. nitens* plantations are grown for pulpwood and are neither thinned nor pruned (Beadle et al., 2007). Small-diameter logs from these plantations are generally unsuitable for production of appearance-grade sawn timber, but are potentially suitable for rotary peeled veneer for use in engineered wood products (Forestry Tasmania, 2007).

Tree breeding is one option for improving tree, log and wood characteristics, so as to achieve a consequent improvement in final product performance. Previously there has been extensive research on breeding objectives and genetic improvement of *E. nitens* for the pulp and paper industry (Hamilton and Potts, 2008, Borralho et al., 1993, Greaves et al., 1997b, Stackpole et al., 2010).

The profitability of producing unbleached eucalypt kraft pulp for the paper industry is affected by log volume production per hectare, basic density and kraft pulp yield (KPY) (Greaves and Borralho, 1996). Basic density is a physical property of wood, dry weight per unit green volume, whilst KPY represents the dry weight of recovered pulp per unit input of dry wood. The product of these two wood properties (basic density multiplied by KPY) is pulp productivity, the total amount of pulp produced per unit of green wood volume, which is used to predict the quality of pulpmill feedstock (Greaves et al., 1997b). In recent years near infra-red reflectance (NIR) spectroscopy on ground woodmeal samples has been used to predict KPY and cellulose content (CC) and these predictions are based on calibrations developed from large numbers of samples that have been chemically digested to determine their CC or KPY. Cellulose content can be determined from chemical

analysis of a 1 g sample (Wallis et al., 1997), whereas laboratory determination of KPY requires a large sample of about 10 kg of wood, and careful sub-sampling is required to obtain the matching woodmeal sample for NIR spectroscopy (Wallis et al., 1997, Downes et al., 2009). Kraft pulp yield and CC are strongly correlated, with phenotypic correlations between them as high as 0.93, since cellulose is the most important constituent of paper pulp by weight (Downes et al., 2007).

While breeding objectives for softwood solid-wood products have been established (Ivkovic et al., 2006a, Wu et al., 2007), similar objectives have not yet been defined for solid-wood products from temperate eucalypts in Australia (Raymond, 2002, Hamilton and Potts, 2008, Hamilton et al., 2009b). To establish a multi-trait breeding objective for a production system focussed on providing *E. nitens* logs for engineered wood products, with pulpwood as a by-product, would require extensive bio- economic modelling (Borrallho et al., 1993, Greaves et al., 1997b). This is a difficult challenge, given that use of this species for these products is not yet commercially developed and potential markets are poorly understood. Traits affecting log volume production (e.g. survival and growth) as well timber recovery (e.g. log diameter) will clearly affect the profitability of tree growing for the production of solid-wood (Wood et al., 2009) and need to be represented in solid-wood breeding objectives. Traits linked to solid-wood product performance and value, such as wood strength and appearance characteristics affecting the marketable product grade will also be of interest to producers of peeled veneer (Farrell et al., in-press). Wood basic density and KPY are likely be included in solid-wood breeding objectives, because in most circumstances, plantation thinnings and/or mill waste will be processed for pulp (McKenzie et al., 2003a).

Wood stiffness is increasingly being recognised as important by both tree growers and engineered wood product manufacturers. Stiffness is the factor which determines veneer sheet stress grade (Standards Australia/Standards New Zealand, 2008) and thereby plywood board strength (Meder et al.,

2002). In rotary peeled veneer sheets, stiffness is measured as dynamic modulus of elasticity (MOE_{dyn}), which is strongly correlated with static modulus of elasticity (MOE_{stat}) (Ilic, 2001) and is one of the most important mechanical properties for solid timber applications (Yang and Evans, 2003). Dedicated in-line processing equipment can be used to assess wood stiffness during veneer sheet production, or after sheets have been peeled. A recent study which evaluated rotary peeled veneer from 21-year-old plantation-grown *E. nitens* found that MOE_{dyn} varied significantly in both radial and longitudinal directions within the tree. Outer heartwood displayed higher stiffness than the inner heartwood, and stiffness increased from the base of the log to a height of 6 m (Blakemore, 2010).

Tree breeders wishing to improve wood properties seldom wait until harvest-age before selecting favourable genotypes for further breeding or deployment. Instead, they identify superior individuals based on selection criteria (i.e. traits that can be cheaply assessed at a young age) which, ideally, are strongly genetically correlated with the harvest-age objective traits (Ponzoni and Newman, 1989, Hamilton et al., 2010). To address a multi-trait improvement objective, breeders must estimate the strength, stability and direction (+/-) of the genetic correlations between selection criteria and all chosen objective traits (White et al., 2007).

Standing tree acoustic wave velocity (AWV) can be used as a predictor of wood stiffness. It is derived from the time of flight of an introduced stress wave signal passing between two transducer probes. Commercially available tools allow a large number of trees to be assessed per day. In *E. nitens* logs resonant acoustic wave frequency has been shown to be strongly and positively correlated with sawn-board static modulus of elasticity (Farrell et al., 2008, Blackburn et al., 2010), and this relationship has been demonstrated in a number of other tree species (Carter et al., 2006, Dickson et al., 2003, Dickson et al., 2004). Log acoustic wave velocity can be measured quickly using commercially available tools, allowing a large number of logs or billets to be quickly assessed and assigned to potential

stiffness categories in manufacturing (Farrell et al., 2008). Acoustic wave velocity in logs and the stiffness of laminated boards has also been found to be closely related (Meder et al., 2002, Thomas et al., 2009) and previous mill studies have confirmed the strong relationship between log AWV and wood stiffness (Dickson et al., 2005, Carter et al., 2006, Farrell et al., 2008).

In studies on the prediction of MOE from microfibril angle and density in *E. globulus*, Yang and Evans (2003) showed that density alone accounted for 81 percent of the phenotypic variation. This strong phenotypic relationship is reflected in the strength of the genetic correlation between these traits observed in the Blackburn et al. study (2010), indicating basic density could be used as a selection criterion for improving wood stiffness. As density also contributes to pulp productivity this would also be a desirable outcome for pulpwood production. Previous studies on trees from unpedigreed *E. nitens* plantations at two locations in Tasmania showed that there was a significant correlation between standing tree AWV and KPY (Downes et al., 2008). If such phenotypic relationships are reflected in genetic correlations, standing tree AWV could potentially be adopted as a selection criterion for KPY. Furthermore, the key wood properties stiffness and density (White et al., 2007) and KPY (Hamilton et al., 2009) are highly heritable, and if strongly correlated with standing tree AWV, improvements in these traits could also be made by the adoption of standing tree AWV as a selection criterion in tree breeding programs (Walker, 2006).

The aim of this study was to estimate heritabilities and determine the strength of genetic correlations between harvest-age DBH and the likely objective traits veneer stiffness, basic density and KPY in plantation grown *E. nitens* processed for rotary peeled veneer. Tree selections were made from a sixteen-year-old *E. nitens* progeny trial by research staff at Forestry Tasmania and the trial was conducted by staff at Forestry Tasmania and the University of Tasmania's Centre for Sustainable Architecture in Wood. Results from the trial and from wood sampling of disks extracted from selected trees were subsequently made available to the author of this thesis,

who analysed the data to determine whether these traits are under genetic control at the race and within-race level. Further aims of the study were to assess the utility of standing tree AWW for improving plantation grown *E. nitens* for rotary peeled veneer products and for pulpwood, and examine whether it would be feasible to breed so as to simultaneously improve traits favourable for both pulpwood and rotary veneer products.

6.2 Materials and methods

6.2.1 Progeny trial

This study was undertaken on an *E. nitens* base-population progeny trial established in 1993 near Tarraleah (latitude 42°18' S, longitude 146°27' E) in central Tasmania. The soil is derived from Jurassic dolerite in the category described as red to brown clayey soils under wet forest (Grant et al., 1995). Previous land use on the site was a radiata pine plantation. The trial site was 600 m above sea level with a mean annual rainfall of approximately 1 200 mm. Trial planting used open-pollinated seed from 420 native-forest parent trees, sampled from twenty-eight localities extending over most of the natural range of *E. nitens* in the Central Highlands region of Victoria. Genetically they encompassed three distinct races: Southern, Northern and Connor's Plain (Dutkowski et al., 2001).

The trial used an Alpha design, a type of resolvable incomplete block design (Paterson and Williams, 1976) with six replicates. Within each replicate 420 families were each represented by a single five-tree line plot, with replicates laid out in 21 incomplete blocks containing 20 family plots per incomplete block. Spacing at planting was four metres between rows and two metres between trees within rows. Fertiliser (100 g of superphosphate and 125 g of 20:10:0 N:P:K) was applied to each tree three months after planting. No thinning or pruning was undertaken in the trial. This study utilised trees from three replicates. Three other replicates had been previously felled as part of an earlier sawmilling study by Blackburn et al. (2010).

6.2.2 Tree assessment, selection and processing

At age fifteen years, all surviving trees in the three remaining trial replicates were measured for diameter at breast height (DBH - 1.3 m above ground over bark) and assessed on a 1-6 visual scale for stem straightness using a methodology purposely designed for Forestry Tasmania's tree breeding program (Blackburn et al., 2011a). To examine wood property traits, only trees with a DBH exceeding 23 cm and with straight stems in the lower 2.6 m of the harvested log were deemed suitable for peeling. In total, 548 trees from 110 families, with five trees from each family (except for two families with four trees each) were selected. As far as possible, families were evenly represented across all three trial replicates.

Selected trees were felled at an average stump height of 0.25 m and a 5.6 m butt-log was extracted and debarked. Before forwarding the butt-log to the plantation landing a disk approximately 50 mm thick was cut from the upper (small-diameter) end of each log. Tree identities were maintained through harvesting and log-yard handling using the method outlined in Blackburn et al. (2011b). Logs were freighted to Ta Ann's Southwood rotary veneer mill in Southern Tasmania. At the mill, a 2.6 m billet was cut from the lower large-end of each log. Billets were peeled to maximise the recovery of long-grain sheets (wood grain parallel to longest dimension), clipped every 1.2 m to produce a standard 1.2 x 2.4 m sheet. Target peeling thickness was 2.6 mm to produce a sheet of 2.4 mm. During peeling, tree identity was maintained on veneer sheets using a Spray Veneer Tracker developed by the University of Tasmania's Centre for Sustainable Architecture with Wood. Because of difficulties with securing small plantation diameter billets in a rotary peeler lathe designed for much larger sizes and the lack of steam softening prior to peeling, some billets could not be processed, and the number of sheets extracted per billet varied. Sheets for assessment were recovered from a total of 410 trees, ninety-nine families being represented by three or more trees.

6.2.3 Assessment of acoustic wave velocity and stiffness

Before felling, a FAKOPP™ microsecond (single pass) timer was used to measure the ‘time-of-flight’ of a stress wave between two probes located 0.5 m and 1.7 m from the base of each selected tree, the upper probe being positioned directly above the lower. Standing-tree AWW was calculated from the stress-wave flight time and known distance. After felling and de-barking in the field, but prior to forwarding to the log landing, log lengths were measured and a DIRECTOR HM200™ ‘Hitman’ instrument was used to predict log AWW. This method was also used to predict AWW of the 2.6 m billets at the mill before peeling. After peeling, veneer sheets were dried to 6-8% moisture content in the mill and plastic-wrapped for transport to Carter Holt Harvey at Nangwarry South Australia, for scanning on a Metriguard DME 2800™, which uses an algorithm to estimate rotary peeled veneer sheet MOE_{dyn} from measured ultrasonic velocity with adjustments for sheet specific gravity (density), moisture content and temperature. Only the first full sheet successfully peeled from the billet’s outer circumference was used for the assessment of MOE in this study. On some billets, one or more sheets broke apart and could not be recovered, so the second or third sheet was used. The outermost sheet peeled from a billet 230 mm in diameter reduced the radius by only about 5 mm, and the second sheet would sample the wood another 5-6 mm further in towards the pith. The small change in radial position, caused when the second or third sheet rather than the first was sampled, was considered likely to have only a small effect on estimated MOE.

6.2.4 Assessment of basic density

After extraction from the log’s upper end, disks were double-wrapped in plastic to prevent moisture loss and stored in a cold room at 2°C. Within two months, the disks were band-sawn to extract two pith-to-bark wedge sectors of approximately 30 degrees. One wedge from each tree was used to determine basic density using the water displacement method (TAPPI, 1989).

6.2.5 Assessment of kraft pulp yield and cellulose content

A pith-to-cambium wafer approximately 10 mm wide was band-sawn from the sample disk. The wafer was air-dried to approximately 12% moisture content and ground to woodmeal using a 3383-L30 Wiley Mini Mill. A

Bruker MPA FT-NIR instrument was used to collect NIR spectra across a wave number range 12 000–4 000 cm^{-1} , at an optical interval of 8 cm^{-1} .

Spectral analysis was performed within the Bruker QUANT routine, within the OPUS 5.5 software package (Bruker, 2005). From the analysis, KPY and CC were predicted using existing NIR calibration models developed from woodmeal of known KPY (Kappa 18) and CC (Downes et al., 2009, Downes et al., 2010).

6.2.6 Statistical analyses

For DBH and stem straightness assessed on all trees within three replicates, univariate restricted maximum likelihood analyses were carried out using ASReml 2.0 software (Gilmour et al., 2006). The following linear model (6.1) was fitted:

$$Y = \text{MEAN} + \text{REP} + \text{RACE} + \text{IBLOCK}(\text{REP}) + \text{PLOT}(\text{IBLOCK}) + \text{FAMILY}(\text{RACE}) + \text{RESIDUAL} \quad (6.1)$$

where Y is the observation, MEAN is the mean, REP is the fixed replicate effect, RACE is the fixed race effect, *IBLOCK*(REP) is the random incomplete block within replicate effect, *PLOT*(IBLOCK) is the random plot within incomplete block effect, *FAMILY*(RACE) is the random family within race effect and *RESIDUAL* is the residual.

Trees selected for the veneer trial represented a sub-set of the entire progeny trial, therefore terms for *IBLOCK*(REP) and *PLOT*(IBLOCK) were omitted from model (1) for the univariate analysis of all AWV and wood property traits. The significance of the RACE term for each trait was gauged with a Wald F-test, where *FAMILY*(RACE) was the error term and the

approximate denominator degrees of freedom were computed using the numerical derivatives method (Gilmour et al., 2006).

To estimate genetic parameters, a series of trivariate analyses, in which covariances among traits for random terms were allowed to vary, were undertaken. Trivariate analyses included DBH, stem straightness and the trait for which parameters were being estimated as response variables. Diameter at breast height and stem straightness were assessed on all surviving trees. Trivariate analyses were undertaken instead of univariate analyses in an effort to account for possible bias in variance component estimates introduced through the selection of stems suitable for rotary peeling (Wei and Borralho, 1998). It was not possible to fit multivariate models including more than three traits due to convergence difficulties. In the trivariate models, plot and incomplete block terms were fitted for DBH and stem straightness only.

The additive variance (σ_{add}^2), phenotypic variance (σ_{pheno}^2) and open-pollinated narrow-sense heritability (h_{op}^2) were estimated for each trait as follows:

$$\hat{\sigma}_{\text{add}}^2 = \frac{\hat{\sigma}_{\text{fam}}^2}{r} \quad (6.2)$$

$$\hat{\sigma}_{\text{pheno}}^2 = \hat{\sigma}_{\text{fam}}^2 + \hat{\sigma}_{\text{residual}}^2 \quad (6.3)$$

$$\hat{h}_{\text{op}}^2 = \frac{\hat{\sigma}_{\text{add}}^2}{\hat{\sigma}_{\text{pheno}}^2} \quad (6.4)$$

where σ_{fam}^2 , and $\sigma_{\text{residual}}^2$ are the variance components for *FAMILY(RACE)*, and *RESIDUAL* respectively, r is the coefficient of relationship among individuals within open-pollinated families, set at 0.4 to account for an

assumed selfing rate in open-pollinated families of 30% (Griffin and Cotterill, 1988).

As an indicator of relative responses to selection among traits (Houle, 1992), percentage coefficient of additive variation (CV_{add} %) was also estimated for each trait using the following:

$$CV_{add} \% = 100 \times \frac{\sqrt{\hat{\sigma}_{add}^2}}{\bar{x}} \quad (6.5)$$

where σ_{add}^2 is as defined previously and \bar{x} is the mean. The significance of the family variance was tested using a ‘one-tailed’ likelihood ratio test (Self and Liang, 1987).

Bivariate analyses were undertaken to estimate pair-wise covariances among random terms. Inter-trait additive genetic correlations (r_a) assumed to be equal to family correlations, were estimated according to the following function:

$$r_{a_{12}} = r_{fam_{12}} = \frac{\hat{\sigma}_{fam_{12}}}{\sqrt{\hat{\sigma}_{fam_1}^2 \hat{\sigma}_{fam_2}^2}} \quad (6.6)$$

where $r_{fam_{12}}$ is the *FAMILY(RACE)* correlation between traits 1 and 2, $\hat{\sigma}_{fam_{12}}$ is the *FAMILY(RACE)* covariance component between traits 1 and 2 and $\hat{\sigma}_{fam_1}^2$ and $\hat{\sigma}_{fam_2}^2$ are the *FAMILY(RACE)* variances for traits 1 and 2 respectively.

Significance tests of inter-trait genetic correlations against zero were conducted using a ‘two-tailed’ likelihood ratio test and against one or minus one, as appropriate, using a ‘one-tailed’ likelihood ratio test (Self and Liang, 1987). Inter-trait phenotypic Pearson’s correlations were also estimated and two tailed t-tests were used to test if phenotypic correlations were significantly different from zero.

6.3 Results

There were highly significant ($P < 0.01$) differences among races in DBH, standing tree, log and billet AWW, and a significant ($P < 0.05$) difference among races for NIR predicted CC. Basic density, veneer sheet MOE_{dyn} and KPY were not significantly different at the race level. When compared to the other two races, the Southern race of *E. nitens* had the highest AWW measures and, although there was no significant difference among races, veneer sheet MOE_{dyn} (Table 6.1).

All traits were observed to be under highly significant genetic control at the family within-race level (Table 6.1). Estimated narrow-sense heritabilities were low, 0.16 for DBH, and moderate to high, 0.56, 0.71 and 0.72 for standing tree, log and billet AWW's respectively, 0.47 for KPY, 0.50 for CC, 0.47 for basic density and 0.54 for veneer sheet MOE_{dyn} . Estimated coefficients of additive variation were low for KPY (1.5%) and CC (2.0%); all other traits had low to moderate values (4-11%) with DBH having the highest.

Estimated additive genetic correlations (r_a) between all AWW measures, as well as between the AWW measures and veneer sheet MOE_{dyn} were strong, positive ($r_a = 0.78$ to 0.86) and highly significant ($P < 0.001$) (Table 6.2). Genetic correlations between all AWW measures and KPY and CC were also strong, positive ($r_a = 0.57$ to 0.73) and highly significant ($P < 0.001$). The additive genetic correlation between veneer sheet MOE_{dyn} and KPY was moderate ($r_a = 0.44$) and significant ($P < 0.05$). Estimated additive genetic correlations between DBH and all traits under study were not significant, except for that between DBH and veneer sheet MOE_{dyn} , which was moderately positive ($r_a = 0.53$, $P < 0.05$). Basic density was strong and positively genetically correlated with all AWW measures and veneer sheet MOE_{dyn} ($r_a = 0.75$ to 0.87), and all correlations were highly significant ($P < 0.001$). Additive genetic correlations estimates between basic density and KPY and CC were not significantly different to zero. Phenotypic correlations among traits were generally positive and significant (Table 6.2).

Table 6.1 Race means, P-values (to test the significance of race differences), overall trial mean, additive variance, narrow-sense heritability (h_{op}^2) and coefficient of additive variation ($CV_{add}\%$) for studied traits, with standard errors in parenthesis.

Trait	Race means (SE)			Race P-value	Overall trial mean (SE)	Additive variance (SE)	\hat{h}_{op}^2 (SE)	CV_{add}
	Connors	Northern	Southern					
Basic density kg m⁻³	476.5 (7.24)	468.6 (3.6)	470.4 (2.00)	ns	471.8 (2.77)	358 (111) ***	0.47 (0.13)	4
Standing tree AWV km sec⁻¹	3.31 (0.06)	3.40 (0.03)	3.54 (0.02)	***	3.42 (0.02)	0.034 (0.01) ***	0.56 (0.13)	5
Log AWV km sec⁻¹	3.15 (0.05)	3.18 (0.03)	3.28 (0.01)	***	3.20 (0.02)	0.028 (0.01) ***	0.71 (0.13)	5
Billet AWV km sec⁻¹	3.30 (0.06)	3.37 (0.03)	3.45 (0.02)	**	3.37 (0.02)	0.03 (0.01) ***	0.72 (0.13)	5
Veneer sheet MOE GPa	11.65 (0.39)	11.45 (0.21)	11.75 (0.11)	ns	11.62 (0.15)	1.12 (0.34) ***	0.54 (0.14)	9
NIR Predicted KPY %	52.44 (0.32)	51.95 (0.16)	52.17 (0.09)	ns	52.19 (0.12)	0.70 (0.23) ***	0.47 (0.14)	1.5
NIR Predicted CC %	40.71 (0.31)	40.22 (0.15)	40.65 (0.09)	*	40.53 (0.12)	0.70 (0.21) ***	0.50 (0.14)	2
DBH₁₄ cm	22.52 (0.44)	23.02 (0.27)	24.15 (0.23)	***	23.23 (0.23)	7.14 (1.03) ***	0.16 (0.02)	11
* P<0.05, ** P<0.01, *** P<0.001 ns Not significant								

Table 6.2 Inter-trait phenotypic (above diagonal) and genetic (below diagonal) correlations with standard errors shown in parentheses.

Trait	Standing tree AWV km sec ⁻¹	Log AWV km sec ⁻¹	Billet AWV km sec ⁻¹	Veneer sheet MOE GPa	Basic density kg m ⁻³	NIR Predicted KPY %	NIR Predicted CC %	DBH cm
Standing tree AWV km sec ⁻¹		0.69 (0.04) ***	0.69 (0.04) ***	0.47 (0.05) ***	0.33 (0.05) ***	0.39 (0.05) ***	0.40 (0.05) ***	-0.03 (0.05) ns
Log AWV km sec ⁻¹	0.89 (0.05) ***		0.91 (0.05) ***	0.58 (0.05) ***	0.41 (0.05) ***	0.47 (0.05) ***	0.49 (0.05) ***	-0.09 (0.05) ns
Billet AWV km sec ⁻¹	0.94 (0.05) ***	0.99 (0.01) ***		0.60 (0.05) ***	0.41 (0.05) ***	0.46 (0.05) ***	0.48 (0.05) ***	-0.17 (0.05) ***
Veneer sheet MOE GPa	0.78 (0.11) ***	0.83 (0.08) ***	0.86 (0.08) ***		0.41 (0.05) ***	0.38 (0.05) ***	0.37 (0.05) ***	0.07 (0.05) ns
Basic density kg m ⁻³	0.75 (0.13) ***	0.75 (0.12) ***	0.79 (0.11) ***	0.87 (0.14) ***		0.08 (0.05) ns	0.08 (0.05) ns	-0.01 (0.05) ns
NIR Predicted KPY %	0.73 (0.14) ***	0.57 (0.13) ***	0.66 (0.12) ***	0.44 (0.20) *	0.06 (0.2) ns		0.92 (0.03) ***	0.07 (0.05) ns
NIR Predicted CC %	0.64 (0.14) ***	0.57 (0.13) ***	0.62 (0.12) ***	0.37 (0.19) ns	0.09 (0.22) ns	0.96 (0.02) ***		0.11 (0.05) *
DBH cm	0.19 (0.19) ns	0.35 (0.18) ns	0.28 (0.18) ns	0.53 (0.18) *	0.44 (0.20) ns	0.15 (0.21) ns	0.17 (0.20) ns	
* P<0.05, ** P<0.01, *** P<0.001	ns Not significant							

6.4 Discussion

6.4.1 Genetic variation in traits

Significant differences observed among *E. nitens* races in AWV, DBH and CC indicated improvement in growth, wood stiffness and CC could also be obtained from selection at the race level, although the gains would be small for CC. The Southern race had the highest mean values. These and other traits favourable for solid-wood products have previously been identified as superior in this race, when compared to neighbouring races from Central Victoria (Hamilton et al., 2009b, Blackburn et al., 2010).

Standing tree AWV showed highly significant additive genetic variance, a moderate to high narrow-sense heritability (0.56 SE, 0.13) and moderate coefficient of additive genetic variation (5%), which was comparable to previous results (narrow-sense heritability - 0.85 SE, 0.12) and moderate coefficient of additive genetic variation (5%) from a study of sawn board production conducted in three other replicates of the same trial (Blackburn et al., 2010). Heritability estimates from two other eucalypt species, *E. dunnii* and *E. pilularis*, are also high in the range of 0.42 – 0.65 (Raymond et al., 2008), indicating (providing favourable correlations with other desired traits exist) its potential as a selection tool in tree breeding programs.

In this study, veneer sheet stiffness exhibited a highly significant additive variance, high-moderate narrow-sense heritability and a high coefficient of additive genetic variation (9%), indicating plantation grown *E. nitens* veneer sheet MOE_{dyn} could be improved substantially by selective breeding. This is in agreement with the results of Zhang et al. (2004) who found a low narrow sense heritability, but high levels of additive genetic variation for veneer MOE in fast-growing mid-rotation (36 years) white spruce. An overall mean of 11.6 (SE, 0.15) GPa for MOE_{dyn} seen here was higher than the 10.4 (SE, 0.20) GPa for static MOE, estimated in a sawn-board study conducted using trees from the same trial (Blackburn et al., 2010). Previous studies have

show that MOE_{dyn} , although strongly correlated with static MOE, is usually about 10% higher than static MOE in the same wood sample (Ilic, 2001, Harwood et al., 2005, Blakemore, 2010). In our trial, a contributing factor to the difference in MOE across studies, may be that the veneer sheet under study was in most cases the first whole sheet extracted from the outer periphery of the billet, while the wood in the sawn boards was primarily from the inner part of the log, closer to the pith, which has been shown in *E. nitens* to be lower in wood stiffness (Evans et al., 2000, Blakemore, 2010).

In studies examining the underpinning physics of acoustic stress waves in wood, Wang et al. (2007) results showed tree AWV measurements were significantly higher than AWV in butt logs extracted from those trees. The cause of this deviation was the different acoustic wave propagation mechanisms used. Their experimental data indicating longitudinal time-of-flight stress waves measured in standing trees are dominated by dilatational waves introduced at the start sensor and therefore results cannot be used for directly predicting the wood stiffness in standing trees. However, such bias is not necessarily an issue for tree breeders who are mainly interested in ranking genetic parameter values and/or the correlations between traits. In the log, the acoustic wave resonance method stimulates many acoustic pulse reverberations that are bounded by the logs periphery, which results a robust, repeatable and very accurate velocity measurement (Wang et al., 2007). In the current study the overall mean of standing tree AWV was approximately six-percent higher than log AWV. The ultrasonic propagation time signal used to determine AWV in the veneer sheet and a derived MOE_{dyn} is not constrained by boundary conditions and although a deviation in the relationship with log resonance AWV may exist, this can be ignored for estimating correlations but should be taken into account when considering the actual MOE value.

Mean predicted levels of KPY (52.2 %) and CC (40.5 %) were consistent with previous studies in *E. nitens* (Greaves and Borralho, 1996, Tibbits and Hodge, 1998, Kube et al., 2001b, Kube and Raymond, 2002, Kube and

Raymond, 2005). Cellulose content was similar to that observed (38.9%) in a previous study of trees from the same trial at a younger age of nine years (Hamilton et al., 2009b). Moderate heritabilities and highly significant additive genetic variance showed these traits were under genetic control, but low coefficients of additive variation for predicted KPY and CC (Table 6.1) indicated that response to selection may be relatively small. However, even a small increase in KPY can result in a substantial increase in profitability, as capital and variable operating costs of pulp mills remain the same irrespective of yield (Greaves and Borralho, 1996).

In this study, mean basic density (471.8 kg m^{-3} SE, 2.8), estimated narrow sense heritability (0.47 SE, 0.13) and an estimated coefficient of additive variation (4%) agreed well with estimates made in the same trial at age nine years by Hamilton et al. (2009b) who observed a mean basic density (451.0 kg m^{-3} SE, 2.0), estimated narrow sense heritability (0.42 SE, 0.11) and an estimated coefficient of additive variation (4.4%). There was a close agreement with corresponding estimates made in a sawn-board study on trees from three other replicates in the same progeny trial (Blackburn et al., 2010) with a mean basic density (478.0 kg m^{-3} SE, 4.0), estimated narrow sense heritability (0.41 SE, 0.11) and an estimated coefficient of additive variation (4.7%). Genetic parameters for basic density observed in this trial fell within the range of values reported for *E. nitens* in published studies reviewed by Hamilton and Potts (2008). There are a number of possible reasons for the higher mean values for mean density observed in this study and the sawn-board trial (Blackburn et al., 2010), relative to that in the earlier study reported Hamilton et al (2009). In addition to the age difference, there were differences in sample type (disks versus cores) and sample height (6 m for disks and 0.9 m for cores), as basic density has been shown to increase with height above ground in this species (Blakemore, 2010). The different studies showed very strong stability in the heritability and coefficient of additive genetic for wood basic density over time.

6.4.2 Correlations among traits

The genetic correlations among standing tree AWV, log AWV and veneer sheet MOE_{dyn} , (r_a , 0.76 - 0.99) were strong and significant, indicating that standing tree AWV could be an effective selection trait when breeding for improved veneer sheet stiffness. They were similar to the significant correlations (r_a , 0.92 – 1.05) among standing tree and log AWV and board stiffness, measured as static MOE, in the sawn board study conducted on trees from the same trial (Blackburn et al., 2010). Standing tree acoustic signals were transmitted through the outer periphery of the tree at the same height as the billet used to produce the veneer sheets taken for MOE_{dyn} assessment, which may have improved the likelihood of detecting correlations between standing tree AWV and sheet MOE_{dyn} .

The strongly positive and highly significant estimated additive genetic correlation between basic density and veneer sheet MOE_{dyn} (r_a , 0.87 SE, 0.14) indicated selective breeding for basic density would also improve veneer sheet stiffness. This was supported by a similar strong and highly significant genetic correlation (r_a , 0.62 SE, 0.21) shown between density and static MOE in the sawn board study at the same site. A moderate to strong positive phenotypic correlation between AWV and basic density has been demonstrated in *E. dunnii* (Dickson et al., 2003, Farrell et al., 2008).

This study found weak and non-significant additive genetic correlations between basic density and KPY and between basic density and CC, and in previous studies a significant negative genetic correlation had been observed between these traits (Kube and Raymond, 2005), although this was in a single provenance trial. These findings differ from that of Hamilton et al. (2009b), who found the additive genetic correlation at age 9 years between basic density and CC in *E. nitens* trees in the same trial site as this study was significant and positive at 0.36 (SE, 0.15) and consistent with previous studies in this species (Tibbits and Hodge, 1998). Other studies in *E. nitens* have found a moderate and positive correlation between basic density and chemical pulpwood traits (Hamilton and Potts, 2008, Greaves et al., 1997b).

However, these studies estimated density and KPY from increment cores collected at or near breast height closer to the base of the trees, compared to 6 m tree height in this study. The relatively small sample size for KPY and CC in the current study made it difficult to estimate correlations precisely, and the use of different sets of families in this trial and the earlier Hamilton et al. (2009b) study may have led to differing results. Overall the findings of this study have not clarified the direction of the correlation between basic density and KPY. Conflicting results are reported in the literature and clearly more work is required to better understand the relationship between these key traits.

This study showed a very strong and highly significant additive genetic correlations (r_a , 0.57 – 0.73) between all AWV measures and both KPY and CC. There were no findings in the literature examining this genetic relationship in eucalypts. However, phenotypic studies in unpedigreed plantations of *E. nitens* at two sites in northern Tasmania by Downes et al. (2006) showed a significant relationship between standing tree AWV and KPY (average for both sites R^2 , 0.64) and between log AWV and KPY (average for both sites R^2 , 0.33). In studies on *E. dunnii* Raymond et al. (2010), examined whether a direct relationship between AWV and wood chemistry exists after the effect of wood density is accounted for. Their studies showed strong relationships between AWV and basic density and between AWV and pulp yield, but found the relationship between basic density and pulp yield was not strong. Their study indicated that acoustic tools were detecting differences in the pulp yield. One explanation postulated was that differences in fibre-length were being detected, as fibre yield has been shown previously to have a strong relationship with pulp yield in this species (Muneri et al., 2005).

There was a significant and moderate to strong genetic correlation between DBH and veneer sheet MOE_{dyn} , but genetic correlations between DBH and the other traits under study did not differ significantly from zero. In the only other study found to have examined this relationship, Zhang et al. (2004)

witnessed a negative genetic correlation between veneer MOE and radial diameter growth in plantation grown white spruce. The researchers concluded selection for an increase in wood stiffness may lead to a decrease in wood volume in the next generation. In the study reported here the observed correlation may be an artefact of the strong relationship between the outer radial wood and an MOE value calculated in a sheet from that location.

The genetic correlation between DBH and CC although not significant was positive and this was consistent with the Hamilton et al. (2009b) study at this site and with another *E.nitens* study by Kube and Raymond (2005). Overall these findings suggest that selection for growth would not adversely affect cellulose content.

6.4.3 Implications for the non-destructive assessment of progeny traits

Given that AWW is under genetic control (Table 6.1) and that favourable correlations are observed between AWW and basic density, between AWW and veneer sheet stiffness and between AWW and KPY (Table 6.2), standing-tree AWW could potentially be adopted as a selection trait to simultaneously improve wood stiffness, density and KPY in *E. nitens* breeding programs. The advantages of a standing tree AWW technique over wood sampling are similar to capturing NIR spectra, i.e. lower cost per tree and minimal damage. The high genetic correlation between basic density and veneer sheet stiffness estimated in this study indicates selective breeding for basic density would also improve veneer sheet MOE. Previous breeding programs aimed at increasing density are likely to have also improved wood stiffness, and breeding values for pulpwood and veneer breeding objectives are likely to be complimentary.

Ongoing research should eventually address which is the most suitable non-destructive technique to use at a given site. In the current study it was not possible to determine the genetic correlation between standing tree AWW at

selection age (for example age six) and that at harvest age. This would require longitudinal studies of genetic trials over a period of several years. However, our study of the genetic parameters of harvest-age standing tree AWV and its correlations with other product traits has helped to assess its potential as a selection criterion. Clearly more work on the selection-age, harvest-age standing tree AWV correlation is required to better understand this relationship, and to gauge the performance of standing tree AWV as an earlier age selection criterion in tree breeding programs. If further studies confirm that a strong genetic correlation exists, then standing tree AWV could be considered as an alternative selection criterion to core measurements, in pulpwood breeding programs aiming to improve basic density and KPY.

6.5 Conclusion

The study confirmed that there is a genetic basis to variation in veneer sheet stiffness and the pulpwood objective traits basic density, KPY and CC, and the potential selection trait of standing tree AWV in *E. nitens*. Estimated genetic correlations between standing tree AWV and the objective traits veneer sheet MOE, NIR predicted pulpwood traits (KPY and CC), and basic density were highly significant and strongly positive. Basic density was estimated to be favourably correlated with standing tree AWV and veneer sheet stiffness, but showed no significant genetic relationship with NIR predicted pulpwood traits. The results of this study did not clarify the direction of the relationship between basic density and KPY, a key relationship for which there are conflicting results in the literature. Importantly, there were no unfavourable estimated genetic correlations among studied objective traits, indicating a breeding objective could be developed to include traits that would simultaneously improve desired properties in both pulpwood and rotary peeled veneer engineered wood products. This also suggests past breeding programs for the improvement of pulpwood properties have not adversely affected wood stiffness, a key trait for veneer sheet and sawn timber.

7.0 CHAPTER 7. DISCUSSION AND CONCLUSION

7.1 Introduction

Study of the genetic parameters of wood product traits required a reliable method of tracking hundreds of pedigreed tree selections from genetic field trials through harvesting, transportation and processing. A methodology (Chapter 3) was established to track the identities of individual tree selections from standing trees through harvesting and transportation to the sawmill log-yard and then through sawmill processing to machined timber boards (Blackburn et al., 2011b). In the ‘veneer stiffness and pulpwood’ study (Chapter 6) the first part of this method was successfully used again to track identified standing tree selections to the veneer mill, proving its robustness and potential for adoption for use in similar studies. If tagged logs were missed, the wooden identification tags could pass through sawn-board, veneer sheet or woodchip processing, without damaging the equipment or resulting in the contamination and rejection of a large batch of wood-chips. During veneer sheet production, tree identity was maintained using a dedicated ‘Spray Veneer Tracker’ developed by other researchers at the University of Tasmania (as detailed in Chapter 6).

Ideally, study of the economics of a timber production system should identify the tree, log and wood traits that have most influence on system profitability, and the economic weights for use in a multi-trait breeding objective (Ivkovic et al., 2006a). For the studies reported here, it was not feasible to rank potential objective traits in a quantitative way, because established sawmilling and veneering industries processing plantation-grown *E. nitens* have yet to commence operating in Tasmania. Increased timber volume per hectare and higher wood basic density are desirable for all three *Eucalyptus nitens* production systems considered in this thesis (sawn timber, veneer and pulpwood production) and are expected to be included in any breeding objective for *E. nitens* (Greaves et al., 2004).

Wood stiffness is likely to be included in a breeding objectives for sawn timber and veneer products, but not for pulpwood (Blackburn et al., 2010). Solid-wood processing systems typically require logs to be straighter than some acceptable lower limit, and for some processing systems, further increases in straightness will improve the profitability of processing (Ivkovic et al., 2006a), so stem straightness is also likely to be included. Similarly the percentage pulp yield will have an influence on the economic returns from processing and would be included and weighted accordingly in any breeding objective.

A detailed examination of the relationships between board internal and external checking was examined in a ‘stiffness and checking’ study in Chapter 4. Traits associated with sawn-board recovered volume, such as DBH, stem-straightness and log-end splitting were examined in a ‘sawn timber recovery’ study in Chapter 5. The final study - Chapter 6, looked at whether it is possible to select to improve the key trait ‘stiffness’ measured as dynamic modulus of elasticity in rotary peeled veneer sheets, while simultaneously improving traits such as density and kraft pulp yield favoured by pulpwood breeders.

In the last study (Chapter 6) the selection of trees for processing into veneer sheets was made by research staff at Forestry Tasmania and the trial was conducted by staff at Forestry Tasmania and the University of Tasmania’s Centre for Sustainable Architecture in Wood. Results from the trial and from wood sampling of disks extracted from selected trees were subsequently made available to the author of this thesis.

7.2 Genetic control of selection criteria and objective traits

7.2.1 Analysis of genetic variation

In each of the three timber processing studies reported in this thesis (Chapters 4, 5 and 6), for the analysis of genetic variation in selection criteria and objective traits, genetic variation in the population under study was

partitioned into among race (race level) and within race (family level) parameters. For DBH and stem straightness assessed on all trees in replicates being harvested, univariate restricted maximum likelihood analyses were performed on a linear mixed model that was fitted in ASReml (Gilmour et al., 2006). To estimate genetic parameters in Chapters 5 and 6, a series of trivariate analyses were undertaken including diameter at breast height, stem straightness and the trait for which parameters were being estimated. If individual selection criteria or traits proved to be under genetic control at the family within race level, they were included in multi-trait models to examine the strengths and directions of genetic correlations between them.

Trees for all processing studies, sawn-board studies (Chapters 4 and 5) and the veneer and pulpwood study (Chapter 6), were selected on the basis of DBH and stem straightness and represented a small sub-set of the entire progeny trial. This selection strategy unavoidably reduced the variation in the DBH and stem straightness of stems selected at the race, family and individual tree level. This was reflected in the lack of a significant difference in DBH between the races in selected stems in the sawn-timber recovery study (Chapter 5). If other traits are correlated with DBH, this selection would be expected to reduce variation in these traits (and potentially an ability to detect differences between them).

The statistical methodology was improved in each experimental study as detailed in Chapters 4,5 and 6. The initial study (Chapter 4) discussed the possibility of bias from the univariate approach used in that study. The second study (Chapter 5) introduced the trivariate analysis and mentioned how trivariate analyses were undertaken instead of univariate analyses in an effort to account for possible bias in variance component estimates. While the last experimental study (Chapter 6) further described how covariances among traits for random terms were allowed to vary, when DBH, stem straightness and the trait for which parameters were being estimated as response variables.

To illustrate the potential for percentage gains from a single generation of breeding for each trait studied (Table 7.1) the following formula derived from Falconer and Mackay (1996) was used:

$$\% \text{ gain} = i \cdot CV_a \cdot h \quad (7.1)$$

Where: i = selection intensity in units of standard deviation

CV_a = coefficient of additive variation

h = square root of the narrow sense heritability

A mass selection intensity of 2.47 for a single trait was applied i.e. selection based on the phenotypic performance of individuals in the absence of knowledge of pedigree and equivalent to selecting the best 20 trees from 1 000 trees (1:50) for a particular trait. The calculated percentage gain (Table 7.1) is that estimated from the offspring of the 20 trees if they were to contribute equally as parents in a grafted clonal seed orchard, relative to the initial base population and is an indicator of relative response to selection across different traits, rather than an accurate estimate of potential gain in a commercial breeding programs. In reality, multiple traits are selected for and more sophisticated approaches to selection are adopted (e.g. selection based on Best Linear Unbiased Prediction (BLUP), which utilises known genetic relationships and inter-trait covariances to maximise the precision of estimated breeding values for multi-trait breeding objectives (Borralho, 1995). Equation 7.1 ignores the effect of selection between races, though additional gain would be expected from exploitation of race effects when these are significant. The gain on mean column (Table 7.1) shows the actual gain in units of the objective traits under study that a tree breeder could expect to achieve, by genetic improvement of an individual trait in one generation of breeding at that selection intensity.

Table 7.1 Estimated genetic parameters and potential gains from selection, for all traits under study in this thesis.

TRAIT	race significance	most favourable significant race	races mean range	add variance significance	h^2_{op}	CVadd %	% gain	gain on mean in trait units
DBH year 4 cm	ns	-	11.4 - 11.5	***	0.17	7	-	-
DBH year 9 cm	**	Southern	16.5 - 17.2	***	0.20	10	-	-
DBH harvest-age cm	***	Southern	22.5 - 24.1	***	0.19	9	9.5	2.2 cm
survival binary 1 alive, 0 dead	ns	-	0.86 - 0.87	***	0.25	n/a	-	-
stem straightness score 1-6	***	Southern	3.7 - 4.3	***	0.17	8	8.0	0.3
log taper cm m ⁻¹	***	Southern	0.40 - 0.49	ns	-	-	-	-
log volume m ³	*	Southern	0.23 - 0.25	***	0.20	23	25	0.06 m ³
lower log end-split index	ns	-	0.58 - 0.72	**	0.28	14	18	n/a
upper log end-split index	ns	-	0.78 - 0.80	***	0.46	14	23	n/a
basic density kg m ⁻³	ns	-	471 - 479	***	0.47	5	8.3	39 kg m ⁻³
standing tree AWW km s ⁻¹	***	Southern	3.18 - 3.54	***	0.85	5	-	-
log AWW km s ⁻¹	***	Southern	3.15 - 3.61	***	0.71	5	-	-
sawn board MOE GPa	**	Southern	9.6 - 10.9	**	0.37	8	12	1.2 GPa
veneer sheet MOE GPa	ns	-	11.45 - 11.75	***	0.54	9	16	1.9 GPa
check - wedge internal score 1-6	ns	-	2.13 - 2.46	*	0.20	20	22	0.5
check - wafer internal score 1-6	ns	-	2.45 - 2.58	***	0.52	22	38	1
check - board surface count	ns	-	35.8 - 42.2	*	0.25	28	34	13
check - board surface length m	ns	-	2.91 - 3.17	**	0.27	31	39	1.2 m
NIR predicted kraft pulp yield %	ns	-	51.95 - 52.44	***	0.47	2	3.3	1.7%
NIR predicted cellulose content %	*	Southern	40.22 - 40.71	***	0.50	2	3.4	1.4%
ns Not significantly different from zero, * P<0.05, ** P<0.01, *** P<0.001					N/A Not Applicable			

7.2.2 Genetic variation among and within races

The Southern race was observed to be superior for most selection criteria and objective traits, for the wood properties examined in Chapters 4 and 6, and in the sawn timber recovery study, Chapter 5 (Table 7.1). Previous studies of *E. nitens* races from Central Victoria have identified this race as superior to other races from the region in both growth and wood density (Hamilton et al., 2009b, Hamilton et al., 2008, Hamilton, 2007a). Race composition in the base progeny trial was approximately 58% Southern, 33% Northern and 9% Connor's Plains. The sawn-board and pulpwood and veneer stiffness studies used selected trees comprising of approximately

81% Southern, 14% Northern and 5% Connor's Plain. In the three processing studies, all selection criteria and all the objective traits, except log taper and green board volume, were shown to be under significant genetic control at the family within race level.

The Southern race had the highest MOE mean values for both final products under study; EcoAsh™ sawn-board (Chapter 4) and the rotary peeled veneer sheet (Chapter 6), although only the log AWV and sawn-board static MOE were shown to be significantly different at the race level. All measures of AWV studied (Chapters 4 and 6) exhibited highly significantly additive variances, high narrow sense heritabilities and high coefficients of additive variation. Similar levels of genetic control were observed for static MOE in the final product EcoAsh™ board (Chapter 4) and dynamic MOE in the rotary peeled veneer sheet (Chapter 6). A study which examined narrow sense heritability of standing tree AWV in two other eucalypt species, *E. dunnii* and *E. pilularis*, (Raymond et al., 2008), similarly found high values of narrow sense heritability and coefficients of additive genetic variation. These results suggest that, provided there are favourable correlations with desired objective traits, standing tree AWV could be an effective selection tool for improving wood stiffness in tree breeding programs.

In the study on sawn board stiffness and checking (Chapter 4), no significant differences in races were observed for all four measures of checking. Within races favourable significant additive genetic variances, moderate to high heritabilities and high coefficients of additive variation for all checking traits under study, indicated selective breeding could reduce checking. However, a reliable predictor of checking with potential for use as a non-destructive selection tool has yet to be found. Observation of internal checking in the extracted wedges indicated that checks were predominantly occurring in the earlywood within individual growth rings. This suggests that internal checking results from variation in collapse, which is supported by the earlier studies of variation in collapse between latewood and earlywood (Chafe et al., 1992) and shrinkage anisotropy (Svensson and Martensson, 1999).

In the sawn timber recovery study (Chapter 5), at harvest age of fourteen years there were no significant race differences for survival with only minor differences in race mean values. However, variation in survival was shown to be highly significant at the family within race level. Coefficient of additive variation estimates and thereby percentage gain predictions were not made for this binary trait.

Highly significant differences between races were shown for DBH at years nine and fourteen (harvest age) in the ‘sawn-board recovery’ study (Chapter 5) and again for DBH at harvest age in the ‘pulpwood and veneer stiffness’ study (Chapter 6). Diameter at breast height was shown to be under low to moderate genetic control in both studies examining this trait (Chapters 5 and 6), with genetic parameters similar to those in previous published studies (Hamilton and Potts, 2008). Both studies showed low coefficients of additive variation and low predicted percentage gains for DBH at harvest age, and similar levels of genetic control were observed in earlier-age DBH in the ‘sawn-board recovery’ study (Chapter 5).

For log volume (Chapter 5) race differences were highly significant with the Southern race having the highest volume recovery. Green-board volume was estimated from log cutting patterns, which were applied to log diameter ranges. The estimated percentage of green board recovered did not increase linearly with increasing log diameter. This may have contributed to the lack of significance in the additive genetic variance that was observed for green board recovery (Chapter 5).

Stem straightness was shown to be under a highly significant level of genetic control at the race level. Within-race genetic control of stem straightness was also highly significant with a heritability similar to that observed in previous studies in *E. nitens* (Hamilton and Potts, 2008). There is no standard means of assessing stem straightness in breeding programs and a number of different approaches are outlined in the literature (Cooper and Ferguson,

1981, Barnes and Gibson, 1986, Cotterill and Dean, 1990). When assessing stem straightness, a compromise needs to be made between the speed/cost of assessment and the precision of individual observations. In reality, the deviation from straightness over a given length of stem is rarely quantified, instead, visual assessment methods that assign trees straightness score categories are used. The method adopted in this study allocated scores based on deviations from stem straightness relative to stem diameter in an attempt to rank trees, while determining their suitability for sawmilling. One potential drawback of this method is that stems of larger diameters are accorded better scores than small trees with the same actual deviation from straightness, potentially resulting in observations that are not normally distributed.

In the Southern race the lower log end-splitting index value was unfavourably marginally higher, although there were no significant differences between races. The incidence of splitting was slightly higher at the upper end of the log and this was consistent with other processing studies in this species (Valencia et al., 2010, Washusen et al., 2007). Highly significant additive genetic variance, moderate heritabilities, high coefficients of variation and high percentage gain predictions were observed for both upper and lower log-end splitting, although the upper end had higher heritability, and a higher coefficient of variation and higher predicted gain levels, when compared to the lower end. Levels of heritability were in the range of similar studies of end-splitting in *E. grandis* (Santos et al., 2004). In this study (Chapter 5) it was noted that due to the production system used in the trial, the volume of sawn-board product lost to end-splitting could not be determined and future studies would be needed to quantify this loss.

Race differences for basic density were not significantly different when studied in three replicates in the ‘stiffness and checking’ study (Chapters 4), or when examined in six replicates of over a thousand trees combining this study with density results from the ‘veneer stiffness and pulpwood’ study (Chapter 6), indicating its relative stability at the race level. Basic density was

estimated from wedges extracted from a disk taken from a height of 6 m, (chapters 4 and 6) and heritability was moderate, with values very similar to those found for core samples from a different set of families from the same trial at age nine years (Hamilton et al., 2009b). The level of heritability was also comparable to those from other studies examining density in *E. nitens*, for example (Greaves, 1997, Kube, 2005, Hamilton et al., 2008) reviewed by Hamilton and Potts (2008).

Of the pulpwood traits, KPY and CC (Chapter 6), only CC was significantly different among races. Within races both traits were shown to be under very similar levels of genetic control. The key objective trait of interest to pulpwood production - KPY, showed a strong to moderate heritability and a highly significant level of additive genetic variance, but a low coefficient of additive variation. Predicted levels and genetic parameters of KPY were consistent with previous studies in *E. nitens* (Greaves and Borralho, 1996, Tibbits and Hodge, 1998, Kube et al., 2001b, Kube and Raymond, 2002, Kube and Raymond, 2005).

7.2.3 Predicted genetic gains

Predicted gains on the mean (Table 7.1) for both sawn-board and veneer sheet MOE suggests good improvements can be made by selecting for these traits. This could prove particularly beneficial for *E. nitens* veneer products as a recent study by Farrell et al. (in-press), has shown that engineered plywood structural products from this species have wood stiffness values that are only marginally acceptable for current markets. Improved stiffness could therefore result in their wider acceptability in the market. Predicted reductions in sawn-board checking indicate a substantial reduction in the incidence of this undesirable trait could be made, although additional costs would be incurred by having to assess this trait destructively by felling the tree, or in disks at a later harvest age, as to-date an earlier-age non-destructive method remains undiscovered. Density and DBH showed similar predicted gains compared to those from earlier studies on *E. nitens* by Greaves (1997). A low level of predicted gain on the mean for stem straightness indicated breeding would

only result in a small improvement in this trait. However, a small improvement might be sufficient to re-allocate a significant proportion of the logs in a plantation to potentially higher-value solid-wood processing although careful consideration must be given to the overall trial mean and its correct determination in pre-assessment stem straightness validation. There was a low percentage gain for KPY, which has been found in other studies of this species (Kube and Raymond, 2001, Kube, 2005, Greaves et al., 1997b) indicating it would be difficult to achieve major improvements through selective breeding, but the financial return from even a small percentage increase would likely justify the inclusion of a trait in any breeding objective.

7.2.3 Inter-trait genetic correlations

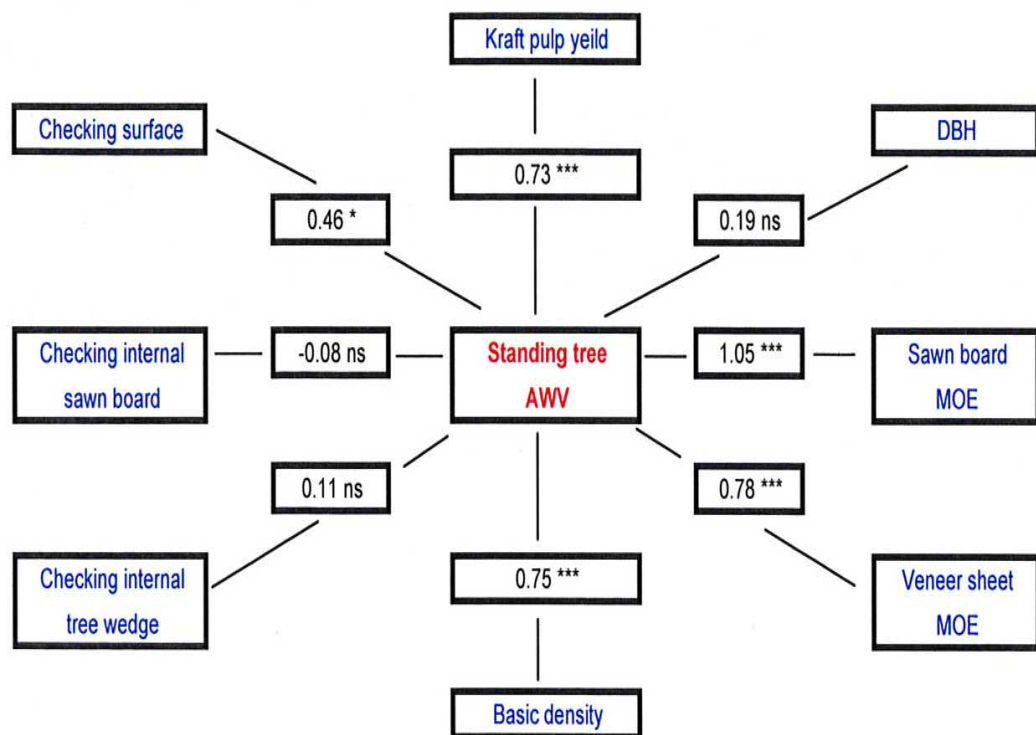
Economic improvement in a defined multi-trait breeding objective can be more easily met if the objective traits are favourably correlated with each other (White et al., 2007). Selection for these traits will then achieve larger gains, improving the quality of the tree to provide a higher value timber resource for all targeted products.

In the ‘stiffness and checking’ study (Chapter 4) and the ‘pulpwood and veneer stiffness’ study (Chapter 6), strong, positive and highly significant estimated genetic correlations were shown between standing tree AWV and the objective traits; log and billet AWV, board static MOE, veneer sheet MOE, density, and the pulpwood objective traits KPY and CC; suggesting that standing tree AWV could be used as a selection tool for these traits in tree breeding programs. Other phenotypic studies have also shown strong relationships between standing tree AWV and MOE at a later age in this species (Valencia Baier, 2008) and in studies on *E. dunnii* (Dickson et al., 2003), researchers demonstrated positive and highly significant phenotypic correlations at ages nine and twenty-five.

The phenotypic correlations between log AWV and board static MOE, billet AWV and veneer sheet MOE shown in these studies supports the studies of Farrell et al. (2008), who demonstrated the segregation of *E. nitens* logs for

stiffness using AWV tools. This was further supported by Dickson et al. (2003) in a study on *E. dunni*, where the phenotypic correlation between log AWV and MOE was positive, high and highly significant. This suggests logs could be selected for improved veneer sheet stiffness and higher KPY prior to processing, either at felling or in the sawmill log yard.

The studies reported in this thesis have shown standing tree AWV has much potential as a key selection criterion in future tree breeding programs. The figure below (Fig. 7.1) shows the additive genetic correlations between standing tree AWV and objective traits relevant to production systems under study in this thesis.



* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, ns Not significant

Figure 7.1 Estimated family within race additive genetic correlations between standing tree acoustic wave and both pulpwood and sold-wood traits.

Strong and positive genetic correlations were observed between the wedge and board wafer internal check scores and between the board check count

and board check length surface scores, indicating either measure of internal or surface assessment could be employed to determine the incidence of check. Overall results were encouraging and indicated selective breeding could be used to reduce the incidence of checking. Of the four methods employed, the 'air-dried wedge' extracted from a stem disk after felling, could be assessed at harvest and appeared promising as a pre log-processing predictor of internal checking. However the wedge checking score was not significantly genetically correlated with sawn board surface checking, indicating internal and surface checking may be separate traits. Correlations between wedge checking in the veneering and the sawmilling studies were weak and not significant, but this is likely due to a lack of family overlap between studies.

The sawn timber recovery study (Chapter 5) described how when phenotypic stem straightness scores were adjusted to account for diameter, favourable additive genetic correlations were still evident between stem straightness and DBH. Inter-age genetic correlations for DBH were similar to previous findings for *E. nitens* (Hamilton and Potts, 2008), with results from the study showing that selection for early-age DBH would lead to genetic improvement of stem straightness and log volume. Log-end splitting was shown to be under moderate genetic control, but results indicated selecting to reduce this trait would have adverse effects on DBH and log volume. In the veneer stiffness and pulpwood study (Chapter 6), DBH was significantly positively genetically correlated with veneer sheet stiffness, suggesting selection for growth would also increase wood stiffness. However, phenotypically the result was weak and not significant. Phenotypic studies in white spruce (Zhang et al., 2004) have also shown a weak adverse relationship exists indicating more work is required to test the relationship between these key traits, especially as DBH will be included in most tree breeding objectives.

In these studies age-age correlations could not be determined for basic density, but previous studies by Greaves et al. (1997a) using the same method of assessment (TAPPI, 1989), showed a very high genetic age-age

correlation for this trait in *E. nitens* between years three and seven, which was supported by a pilodyn (a tool used to indirectly assess basic density) study showing significantly high age-age genetic correlations (Greaves et al., 1996). An expected and extremely strong and positive additive genetic relationship between the NIR predicted pulpwood traits KPY and CC (Chapter 6) further supports the use of the more easily analytically assessed CC for effective prediction of KPY. A weak and non-significant additive genetic correlation was observed between density and both NIR predicted KPY and CC (Chapter 6). This is supported by another study in *E. nitens* (Kube and Raymond, 2001), which found a weak and adverse genetic although significant relationship between these traits at three different sites. However, contrary to these findings another study has reported a stronger, positive genetic relationship exists (Hamilton, 2007a).

7.3 Key findings from conducted studies

- The study has shown there is a strong genetic basis to variation in a number of selection criteria and objective traits important for both pulpwood and solid-wood products and that they are amenable to genetic improvement through selective breeding.
- *Eucalyptus nitens* breeding programs targeting pulpwood traits are unlikely to have adversely affected traits favourable for solid wood products.
- Standing tree AWV could potentially be used in future as a selection criterion to improve the objective traits density, wood stiffness and KPY, which are favourable for both solid wood and pulpwood products.
- In future, if favourable age-age correlations can be established, then standing tree AWV could be the most cost effective selection tool in tree breeding programs aiming to improve pulpwood and solidwood value of *E. nitens*.

- Breeding could be used to reduce the incidence of checking in solid-wood products, but the impact of doing so on other wood property traits is largely unknown.
- Assessment of checking can be made at harvest age by sampling disks from felled trees, which would prove more cost effective than check assessment in the sawn-board.
- The genetic correlation between internal and surface checking does not appear to be strong and these traits may be under the control of different genes.
- Earlier-age DBH can be used as a cost effective selection criterion to breed for improved stem straightness and timber volume recovered.
- The incidence of log end-splitting could be reduced by selective breeding, but this would likely reduce DBH and the volume of timber recovered.
- A new method of tracking standing trees through harvesting, log transportation and subsequent sawmill processing was trialled and proved to be successful.

7.4 Concluding remarks

Information resulting from these studies and the examination of genetic parameters obtain from previous studies of traits relevant to pulpwood, sawn timber and veneer production systems suggests earlier breeding programs targeting pulpwood traits have not adversely affected traits favourable for solid-wood products. Non-destructive acoustic wave velocity, tree and wood property assessment methods were investigated and strong evidence was provided to support their use in the selection of trees for processing and in tree breeding programs. Of the methods examined standing tree acoustic wave velocity potentially offers a means of predicting sawn board and peeled veneer objective trait breeding values, although further work is required to establish age-age genetic parameters and prove the technique's suitability as an earlier-age selection tool.

Checking, a major issue in solid wood products processed from *E. nitens* was examined in detail and the studies indicated that checking could be reduced by selective breeding using estimates of checking scores made on dried wedges extracted from tree stem disks at harvest. A non-destructive selection tool to predict checking was not directly identified, although assessment of core-shrinkage was recognised as a possible selection criterion. However, further work is required to improve the precision of genetic correlation estimates between shrinkage in extracted cores and checking assessed in harvest-age disk wedges, and in the final sawn-board product.

In these studies, genetic correlations indicated that breeding to increase basic density directly could adversely affect the amount of surface checking, while there would be no correlated response in KPY. However, previous studies suggested a positive correlation between basic density and KPY, so more research is required to understand these genetic relationships in *E. nitens*.

Genetic variation in and intertrait genetic correlations among timber recovery traits were examined and strong correlations were observed between DBH at earlier ages and both log volume recovery and stem straightness, demonstrating DBH at age four years could be an effective selection criterion to improve log and therefore green board volume and simultaneously improve later age stem straightness. The method of stem straightness assessment used in the product volume recovery study provided results that could be used both for estimates of genetic parameters and directly to identify logs suitable for sawing in the studied production system (logs with straightness category 5 and 6). However, more research is required to determine optimal stem straightness assessment methods for both tree breeding and solid-wood processing.

Provided strengths and directions of genetic correlations between them were favourable, in future breeding programs it would be possible to simultaneously improve the product volume recovered and the wood properties of the wood products; sawn timber, veneer and paper. However, even with advanced statistical software packages it is difficult to obtain reliable genetic correlations between wood product traits estimated from a small and somewhat biased subset of trees, selected from a limited range of DBH and stem straightness, both which have low heritability. The findings from these studies, difficulties in convergence and the non significant results shown in conducted studies, suggests more trees per family and/or more families should be sampled when attempting to establish genetic parameters for wood property traits. However, wood-processing trials are expensive to undertake and difficult to organise logistically, factors which can place severe constraints on the number of trees and families included in such studies.

The work presented in this thesis contributes to the body of knowledge on the genetic improvement of *E. nitens* for both pulpwood and solid-wood production. A major future challenge will be to determine the drivers of genetic variation in checking and establish breeding objectives that will reduce the incidence of checking in solid wood products; while improving both product volume recovery and other favoured wood properties.

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